NASA Space Radiation Program Integrative Risk Model Toolkit

Myung-Hee Y. Kim, Shaowen Hu, Ianik Plante, and Artem L. Ponomarev

Wyle Science, Technology and Engineering, Houston, Texas, USA

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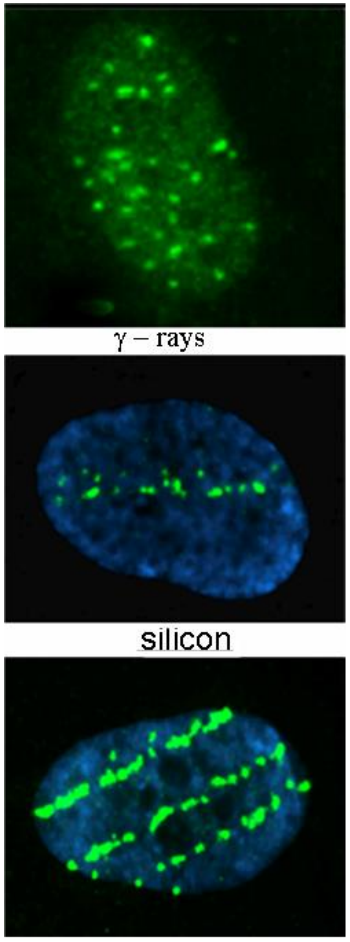
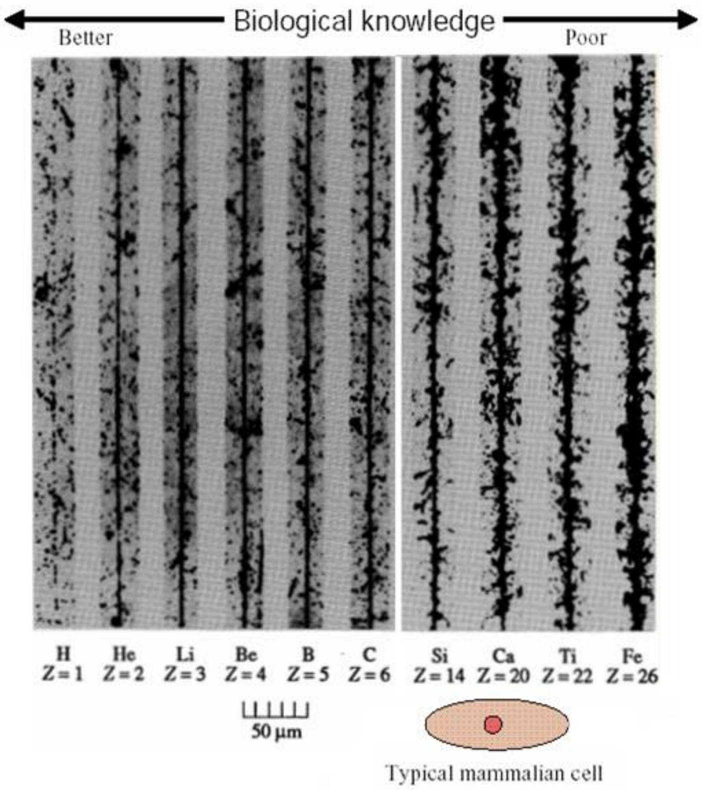
The Space Radiation Problem

- 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





Lancet Oncology (2006)

NASA Space Radiation Risk Tools

- **NSCR 2012**: **N**ASA **S**pace **C**ancer **R**isk 2012
  Projection of cancer risk from exposure to space radiation
- **ARRBOD**: **A**cute **R**adiation **R**isk and **B**RYNTRN (Baryon Transport) **O**rgan **D**ose
  Organ dose projection and acute radiation risk calculation from exposure to SPE (solar particle event)
- **GERMcode: G**CR (Galactic Cosmic Ray) **E**vent-based **R**isk **M**odel (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**: **R**elativistic **I**on **TRACKS**
  Simulation of heavy ion and δ-ray track structure, radiation chemistry, DNA structure and DNA damage at the molecular scale
- **NASARTI: NASA Ra**diation **T**rack **I**mage
  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: Hemo**cyte **Dose**
  Retrospective dose estimation by using multi-type blood cell counts

THE OVERVIEW (HIGHLIGHT) OF TOOLS

NASA Space Cancer Risk (NSCR) 2012

NSCR: 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

NASA Space Cancer Risk (NSCR) 2012

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

- The Runner Up, 2013 NASA Software of the Year, Office of the Chief Engineer, NASA Headquarters, Nov. 26, 2013

Relativistic Ion Tracks (RITRACKS)

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

- ❑ The Honorable Mention, 2012 NASA Software of the Year, Office of the Chief Engineer, NASA Headquarters, Oct. 2012

Acute Radiation Risk and BRYNTRN Organ Dose (ARRBOD)

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*
- ARRBOD v1.0 and v2.0 are NASA milestones for the Office of Management and Budget (OMB) in 2012

Award

- Competed for 2010 JSC Exceptional Software Awards

GCR Event-based Risk Model (GERM) code

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

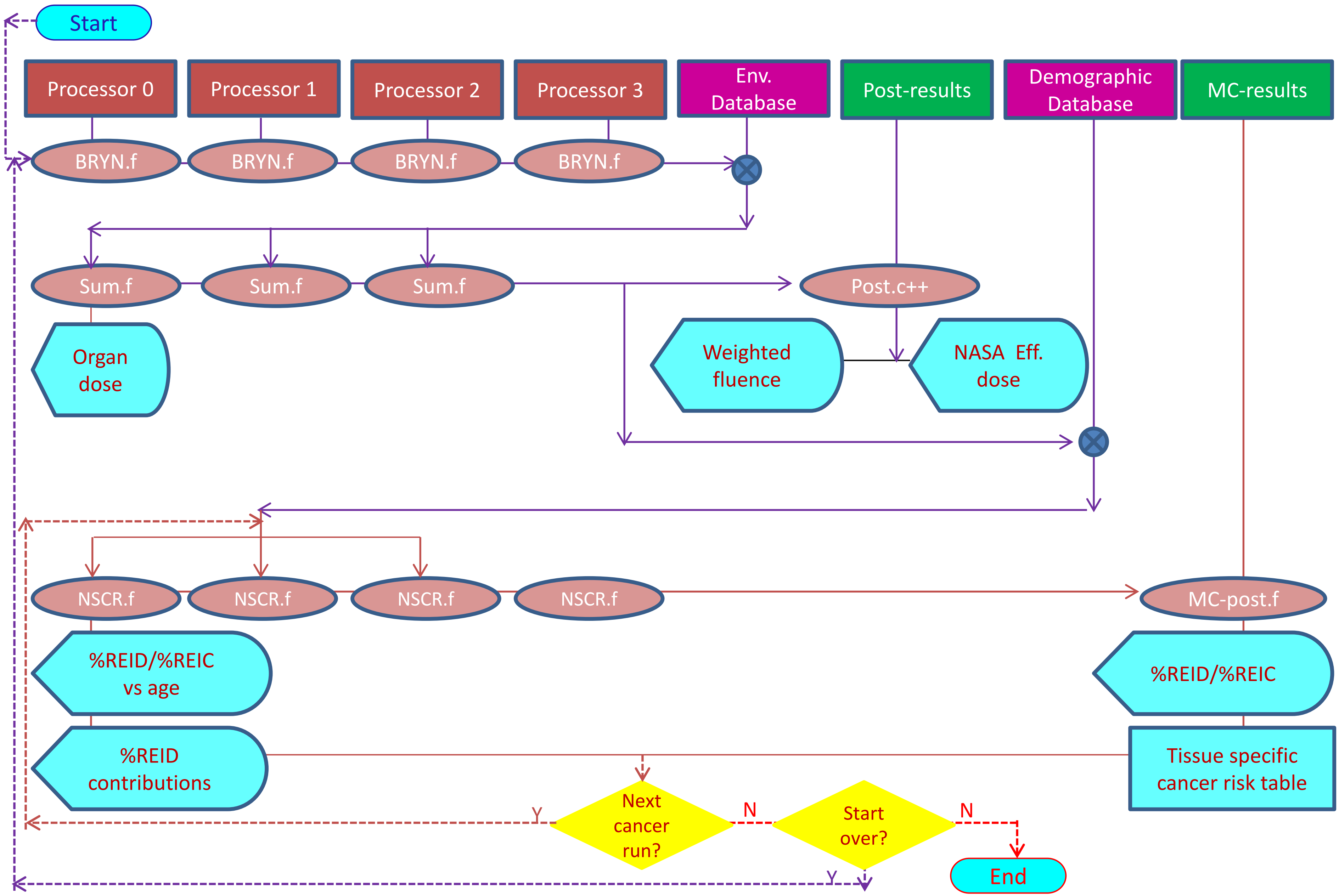
- ❑ The scientists participating in NSRL experiments obtain the data needed for the interpretation of their experiments
- ❑ Ability to model the beam line, the shielding of samples and sample holders
- ❑ Estimate of basic physical and biophysical outputs of the designed experiments

Application of GERMcode to Space Exploration

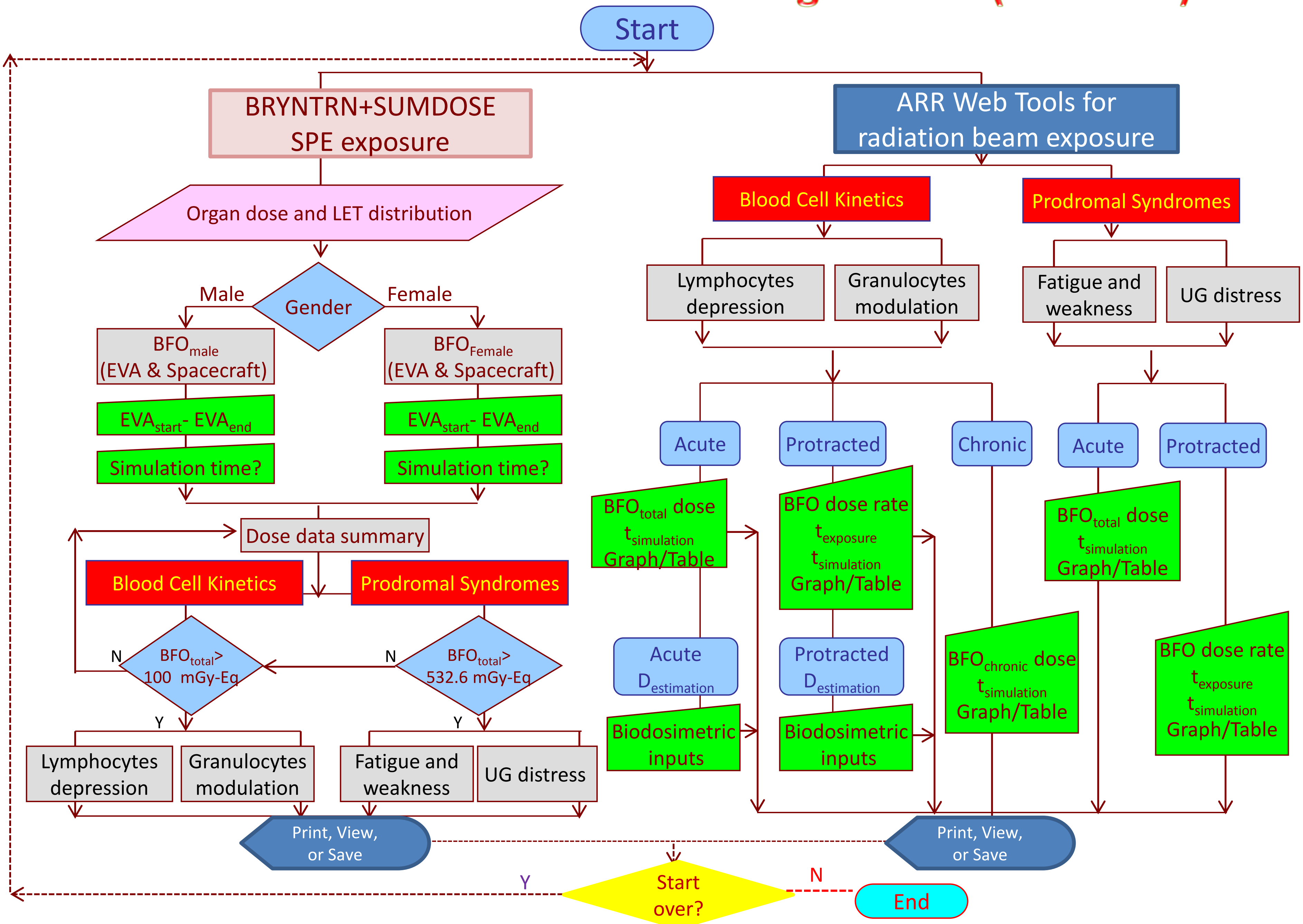
- ❑ Assessment of radiation effect on food and pharmaceuticals during a Mars mission (Kim et al., THREE, Jan. 2015)
- ❑ GCR reference field design for radiobiological research using ground based accelerators (Kim et al., COSPAR 2014)

THE OVERALL I/O SEQUENCES

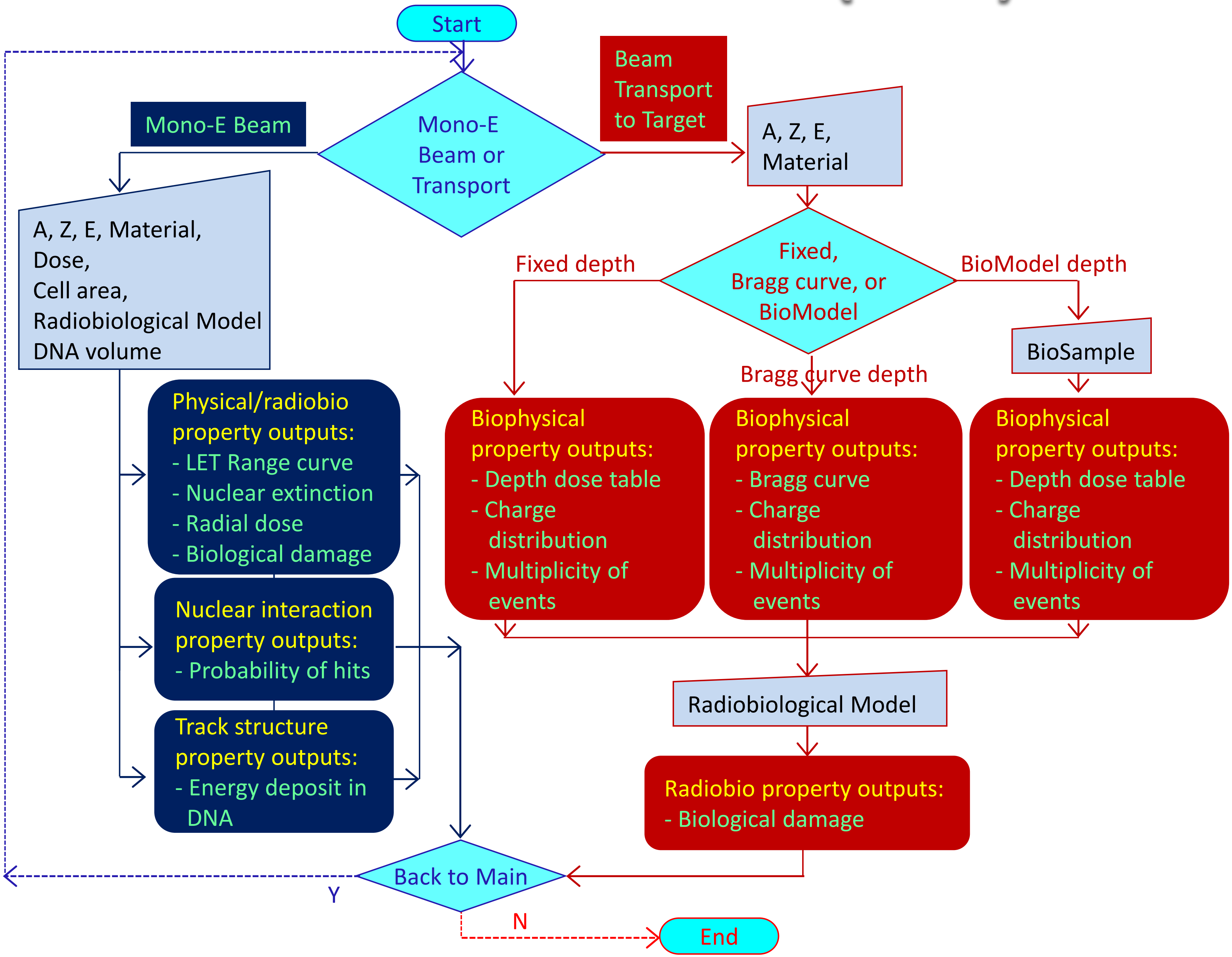
NASA Space Cancer Risk (NSCR) 2012

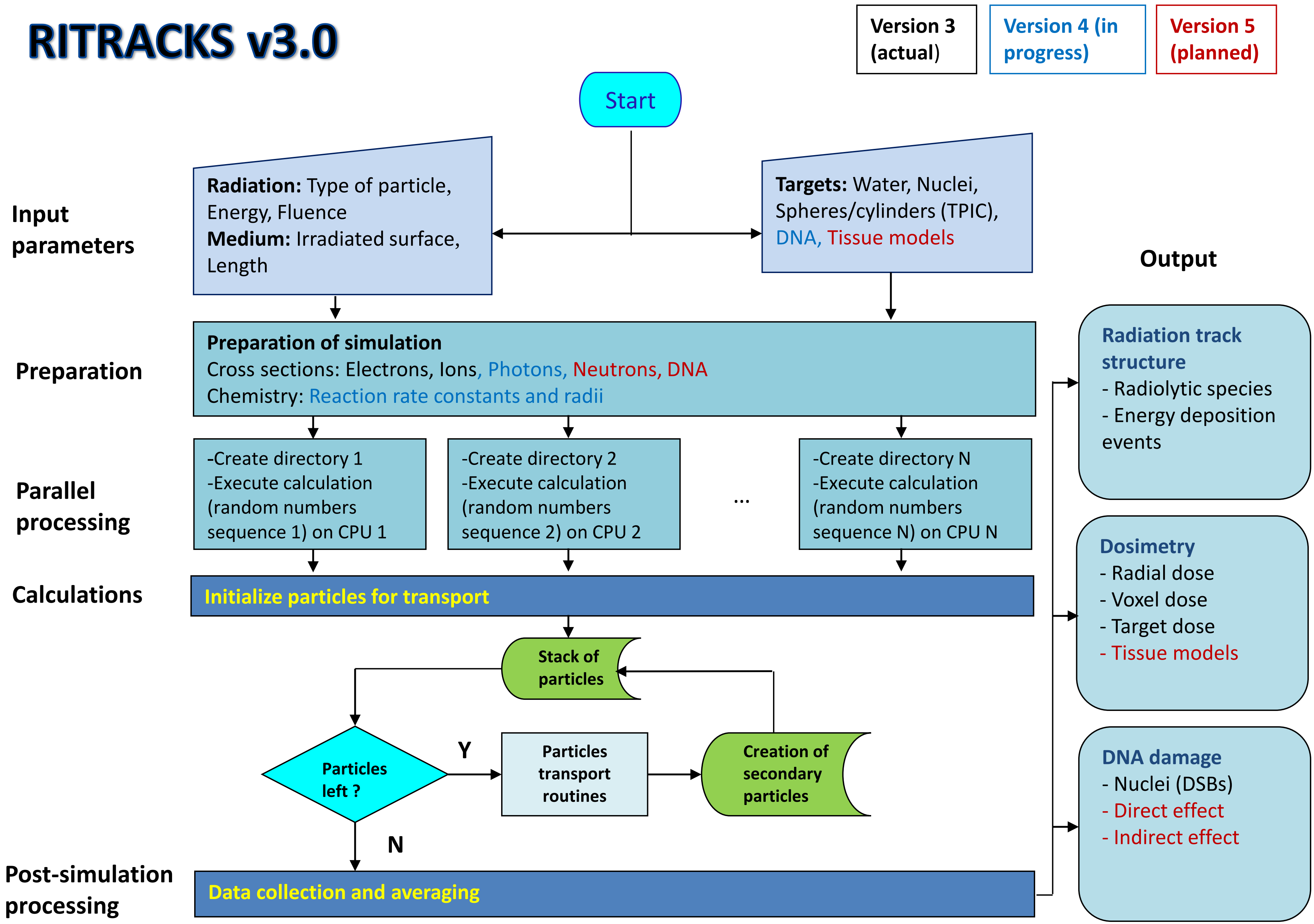


Acute Radiation Risk and BRYNTRN Organ Dose (ARRBOD) v2.0



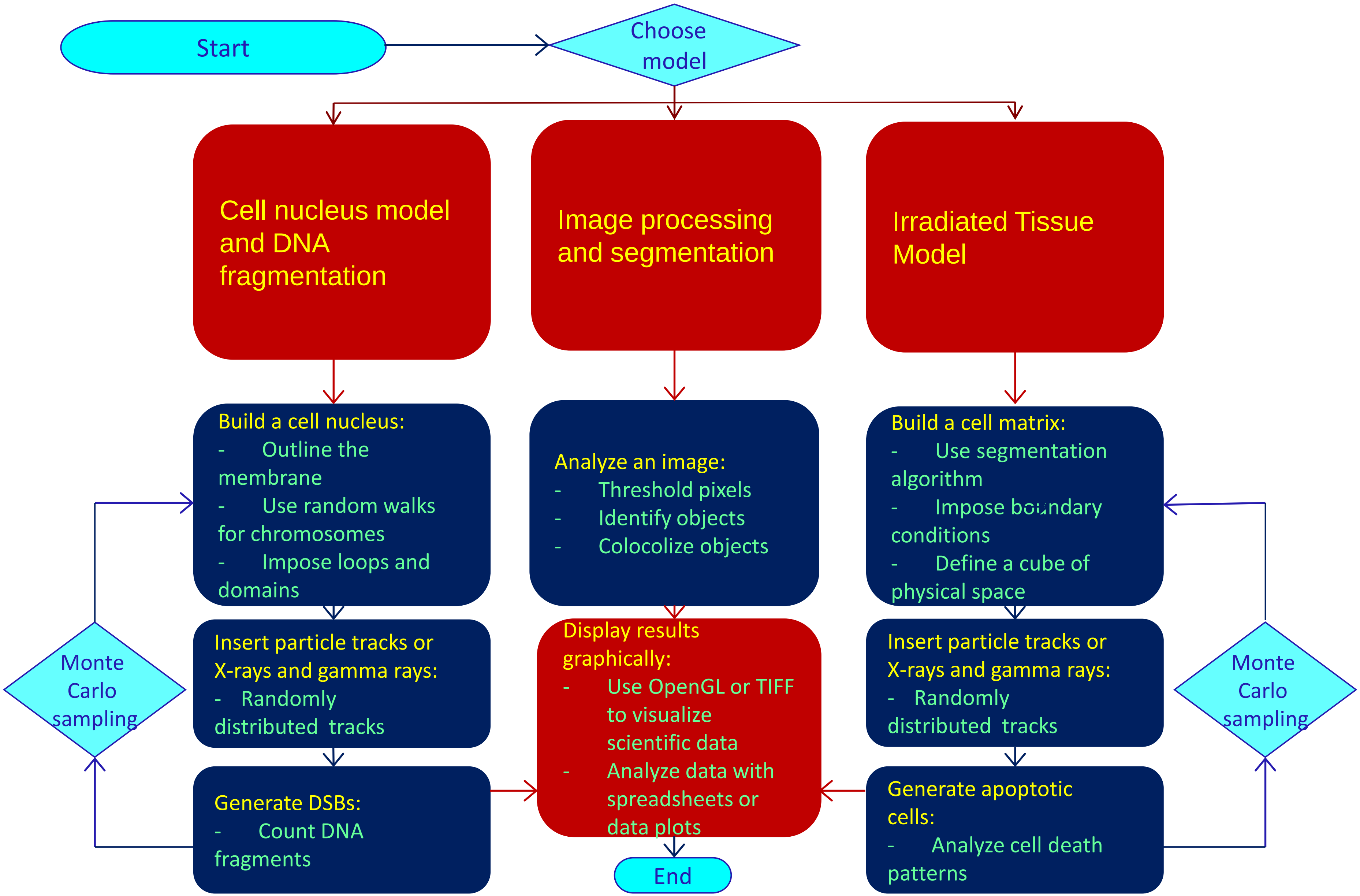
GCR Event-based Risk Model (GERM) v1.1



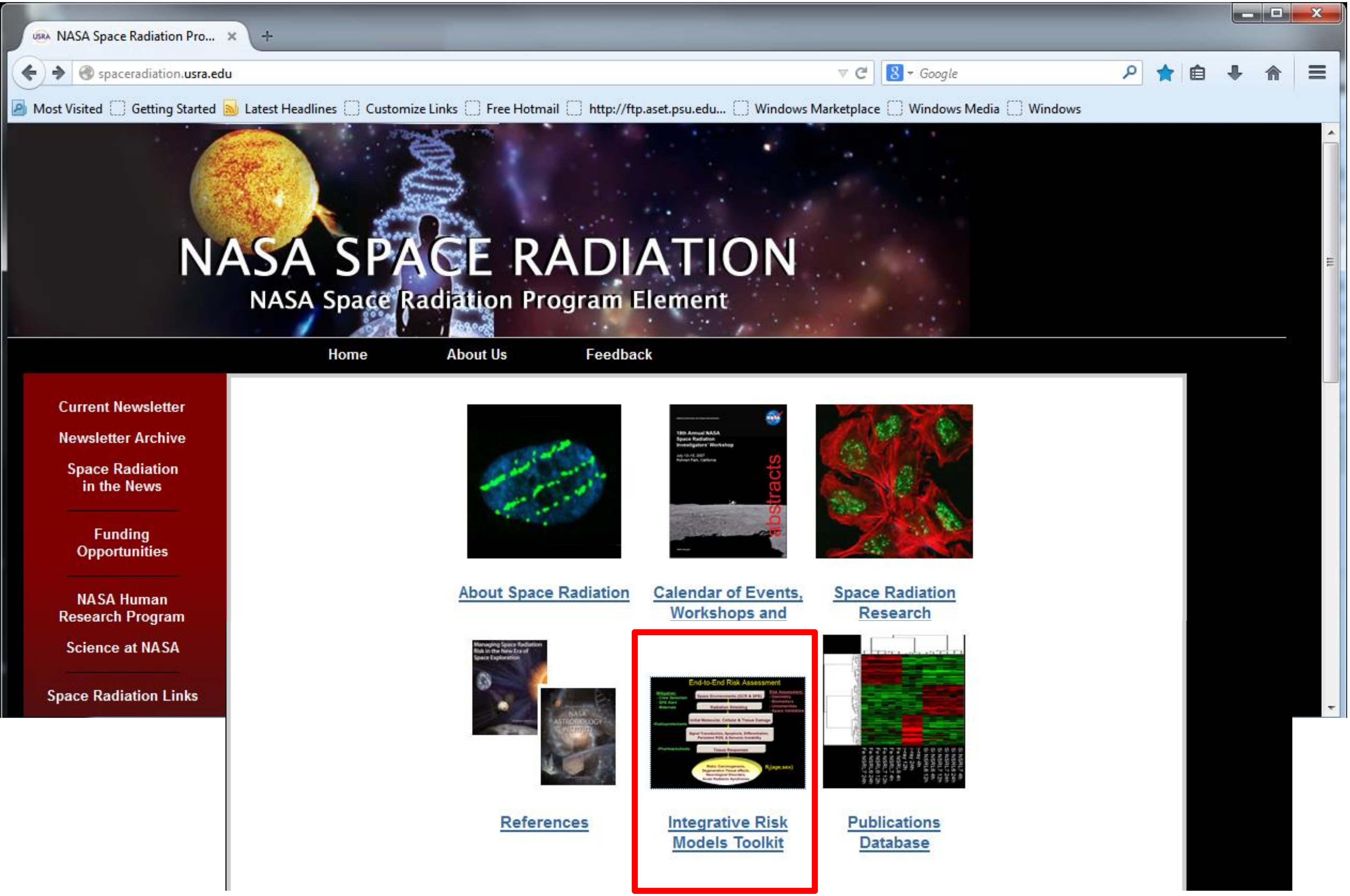


RITRACKS v3.0
Version 3 (actual)
Version 4 (in progress)
Version 5 (planned)
Start
Input parameters
Radiation: Type of particle, Energy, Fluence
Medium: Irradiated surface, Length
Targets: Water, Nuclei, Spheres/cylinders (TPIC), DNA, Tissue models
Output
Preparation
Preparation of simulation
Cross sections: 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
Stack of particles
Particles left ?
Y
N
Particles transport routines
Creation of secondary particles
Post-simulation processing
Data collection and averaging
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



http://spaceradiation.usra.edu/



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.