ARRT Development for the Upcoming Human Exploration Missions

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Abstract The health risks of space radiation present big challenges to space exploration, with the possibility of large Energetic Solar Particle Events (ESPEs) inducing Acute Radiation Sickness (ARS) during upcoming Artemis missions. An operational software Acute Radiation Risks Tool (ARRT) was developed to directly use measurements from onboard dosimeters to project organ doses during times of increased radiation exposure, so that any possible ARS risks of the astronauts can be monitored in real time using a data stream at the astronaut location. To enable ARRT to handle variant scenarios of any possible ESPEs in an automatic manner for mission operation, two data sets were employed in developing its modules, one involving historical solar protons recorded over the past four decades and the other using the real-time telemetry readings of dosimeters onboard International Space Station (ISS). Though vastly different in terms of data cadence, smoothness, and data gaps, all events in these data sets can be correctly processed to output organ doses and ARS risks and generate flight notes for communication within the Flight Control Team (FCT). All these tasks are completed with close interactions between multiple modules developed with many state-of-the-art facilities of full stack web applications. This work demonstrates that ARRT meets the requirement to project radiation exposure and to provide clinical guidelines in very short time steps as the ESPE unfolds, even for the longest event in data sets, making this tool eligible to be tested during the upcoming unmanned Artemis mission and utilized in future space exploration.

Plain Language Summary An operational tool Acute Radiation Risks Tool (ARRT) was developed to directly use the onboard dosimeters’ reading as inputs to estimate organ dose and possible clinical acute effects in case of severe Solar Particle Events (SPEs) for the upcoming Artemis missions. This paper describes all underlying models of the tool, various functions essential to operational management of possible effects, and how they are integrated to run automatically in real time whether the dosimeter readings are at background range or are elevated. A historical data set with recorded 159 significant events is used to demonstrate its flexibility and accuracy to process diverse features of SPEs.

1. Introduction

Leaving the protection of the Earth’s atmosphere and geomagnetic field, astronauts traveling in deep space are at risk from radiation hazards induced by various high energetic particles ubiquitous in our solar system. In the literature, much of the focus has been on the Galactic Cosmic Rays (GCR), which is hard to shield and may induce stochastic late health effects such as cancers that are of postflight concern. Additionally, the intense Energetic Solar Particle Events (ESPEs) can cause Acute Radiation Sickness (ARS) that could manifest during the mission. Previous analyses indicate that ARS symptoms would be generally mild to moderate even in the worst-case Solar Particle Events (SPEs) for crew inside a typical interplanetary spacecraft (Townsend et al., 1991, 2018), but even mild manifestations of fatigue and nausea could make the impacted crew less able to perform required tasks and thus may adversely impact the success of a mission (Hu et al., 2009). As opposed to GCR, SPEs can be effectively shielded against, and recent vehicle designs have incorporated shielding concepts that make use of the redistribution of vehicle mass. An effective warning system for a large SPE could also allow the crew additional time to reconfigure the vehicle volume and reduce their event exposure.

As SPEs are not always directed to the measuring satellites deployed either close to the Earth or in interplanetary space, a practical way to estimate the ARS risks for future exploration spacecrafts like Mars missions...
will be through the use of onboard dosimeters. Using direct measurements, radiation exposure can be monitored both in real time and always along the path of the spacecraft. Such an algorithm has been developed specifically for the Orion Multi-Purpose Crew Vehicle (MPCV) and described in a recent publication (Mertens et al., 2018). This organ dose estimation algorithm involves a fitting procedure between the real-time vehicle dosimeter measurements and a precomputed database of dose quantities calculated from the HZETRN radiation transport code (Slaba et al., 2016; Wilson et al., 2016), considering the actual MPCV vehicle geometry and mass distribution. The paper also described how the estimated organ doses at the crew locations are utilized as inputs to a set of biological response models, which predict clinically critical syndromes associated with ARS and quantify Radiation-Induced Performance Decrement (RIPD; Hu et al., 2009, 2012; Hu & Cucinotta, 2011). The modeled results will provide important information to guide the crew mitigation efforts in case of severe ESPEs through the efforts of Flight Control Team (FCT).

The organ dose fitting algorithm, as well as the biomathematical ARS models, has been incorporated in a software package, the Acute Radiation Risks Tool (ARRT), which is currently planned to test operationally on the National Aeronautics and Space Administration’s (NASA) next unmanned beyond low Earth orbit (LEO) mission (Artemis I at the time of this writing) and will be fully utilized on the following manned beyond LEO mission (Artemis II at the time of this writing; Hu et al., 2020). During a space flight mission, ARRT will be run at the Mission Control Center (MCC), and all its outputs will be automatically produced at the telemetry time cadence of the vehicle dosimeter measurements, which is anticipated in the range of 15 to 30 min. The operationally useful functions of the tool include rendering and plotting the dosimeter readings, detecting the onset and end of an event, calculating and plotting the relevant organ dose quantities, triggering the ARS biological models if threshold is reached, and generating a flight note to facilitate communication of a mitigation response within FCT. This paper attempts to give a summary of these functions and to describe how they are developed in a compact software tool. Section 2 briefly describes the algorithms underlying various models, section 3 summarizes the strategies used to develop various modules and the functions of each module, while section 4 gives examples of the outputs of a historical data set.

2. Modeling Algorithms

This section describes the algorithm of the two main components of ARRT. The method of estimating the ESPE organ doses from the vehicle dosimeter measurements is presented in section 2.1. A brief summary
of the acute biological response model is given in section 2.2, the inputs of which come from the ESPE organ dose model.

2.1. SPE Organ Dose Estimation

ARRT is developed specifically for the Orion MPCV, an interplanetary spacecraft intended to carry a crew of four astronauts to destinations at or beyond LEO. The onboard radiation detection of this spacecraft will be provided by the Hybrid Electronic Radiation Assessor (HERA), which is a distributed dosimeter system based on the coupling of solid-state silicon detectors with the Timepix chips (Kroupa et al., 2015). In the upcoming Artemis I uncrewed flight, one HERA system with three detectors will be deployed at different locations. For Artemis II, the first scheduled crewed mission of MPCV, two HERA systems with six spatially separated sensors will be deployed for more robust measurement (Figure 1).

ESPE effects can be mitigated during the vehicle design process through thoughtful redistribution of mass to provide a secondary role in radiation shielding. The NASA Space Radiation Analysis Group (SRAG) has been closely involved with the design process of the MPCV to identify locations with lower inherent shielding and attempt to improve the overall shielding concept without adding excess mass to the vehicle. In addition to improving the design of the vehicle, a contingency location has been designated where the crew can shelter in the stowage bays of the vehicle, redistributing the mass contained within this area to improve radiation protection (Figure 2).

The algorithm of organ dose estimation from dosimeter measurement has been described in detail in a previous paper (Mertens et al., 2018), which involves the following four major steps:

1. Generate a database of silicon doses at vehicle dosimeter locations and organ doses at the normal crew seat locations as well as the crew locations inside the storm shelter, for 65 historical events with known total spectra.
2. Find the event in database that minimizes the differences between measured and database averaged dose in silicon, whose spectrum thus best matches the spectral shape of the real-time vehicle radiation environment.
3. Find the optimal scaling parameters between the vehicle dosimeter measurements and the precomputed absorbed dose in silicon at the dosimeter locations for the selected event in the historical ESPE database.
4. Apply the scaling parameters to the database of organ doses to obtain real-time organ doses at the normal and storm shelter crew locations.

The reliability of this algorithm was checked with the October 1989 event. Assuming an isotropic distribution of ESPE protons, it was found that the differences are within 2% between the total organ doses predicted by this algorithm and those calculated from the original spectrum of this event, and the uncertainty of organ dose rates is on the order of 25–35% for the 329 time intervals (30 min; Mertens et al., 2018). This study also verified that the additional three vehicle dosimeters in the Artemis II configuration do not improve the accuracy of the organ dose prediction but provide redundancy in the onboard measurements in case one or more of the dosimeters malfunction. Nevertheless, for the Artemis I configuration, if one dosimeter measurement is unavailable, the maximum difference of organ dose rates can reach 54% with two dosimeter measurement, but the uncertainty can be less than 31% if HPU1 is among them. If only one dosimeter is functioning, the error of using the dosimeter readings as organ dose rates can be as high as 20-folds (Mertens et al., 2018).

2.2. Acute Biological Response Models

The prediction of acute biological responses to SPE exposure in ARRT is based on codes developed for ARRBOD and HemoDose (Hu et al., 2015; Kim et al., 2010). ARRBOD includes the neurovascular models (nausea and vomiting, fatigue, and weakness) adapted from the RIPD models (Matheson et al., 1998) and four sets of hematopoietic models, which describe the dynamics of lymphocyte, granulocyte, leukocyte, and platelets in the peripheral blood after exposure (Hu et al., 2015). The HemoDose code is a biodosimetric tool that uses various blood cell counts after exposure to calculate absorbed doses, with a HemoGrade module linking acute and protracted doses with clinical severity scores of hematopoietic ARS, as well as the
dynamics of hematopoietic stem cells in bone marrow (Hu, 2016). The user interface to these models has been modified for this work such that the Blood-Forming Organ (BFO) dose rate provided by the ESPE organ dose estimation algorithm is taken as input at each time point, and outputs are generated along with the real-time update of dosimeter readings.

3. ARRT Development Strategy

This section describes the strategies used in developing various modules of ARRT, which include reading and plotting dosimeter recordings, detecting the onset and end of an event, calculating and plotting the relevant organ dose quantities, triggering the ARS biological models, and generating a flight note for FCT.

3.1. Reading and Plotting Dosimeter Recordings

As meaningful real-time HERA data will not be available until Artemis I and Artemis II start their journeys in space, the development of ARRT must rely on a historical data set and a real-time data set.

The historical data set in ARRT is generated by transport calculation with the SEPEM 2.0 data set (http://www.sepem.eu/), which is a cross-calibrated uniform data set using the Geostationary Operational Environmental Satellite (GOES) measured solar proton fluxes during 1974–2015, with an energy range 5–289 MeV. With segmental spectra (Hu et al., 2016) of 15-min cadence generated from the fluxes as a boundary condition and material and shielding thicknesses determined by ray tracing the computer-aided design (CAD) model of the MPCV for Artemis II (with six HERA sensors), transport calculations through the vehicle are performed by a numerical solution of the one-dimensional Boltzmann transport equation using the HZETRN2015 code (Slaba et al., 2016; Wilson et al., 2016). The resultant data set contains dose rates for the six dosimeters spanning uniformly from 1974 to 2015, with a 15-min cadence.

As the average thicknesses of the six dosimeters in Orion MPCV are around 30- to 45-g/cm² aluminum equivalent (Mertens et al., 2018), it is of concern if proton energies of SEPEM data set are too low for the simulation of the HERA readings during historical SPEs. To verify this, we conducted transport calculations to investigate the segmental spectrum contribution to silicon doses at the locations of these devices, with the Band spectra with energy range 0.01- to 2,500-MeV for nine subevents in 1989 (Raukunen et al., 2018). The results in Figure 3 indicate that, generally, the contributions of the protons in the energy range of SEPEM data set are significantly larger than those of the protons out of the range, implying that the simulated dosimetric profiles with SEPEM data set are sufficient to reflect the time parameters, such as the onsets, the peaks, and the ends, of historical SPEs. However, for the first 75 min of the 29 September 1989 event which has the hardest spectrum among these events, the contribution of the protons with energy >289 MeV is around 46%. Therefore, the simulated dosimetric quantities may not be accurate enough for risk analysis. Because of this shortcoming, a factor input is added in the input panel for the user to adjust the size of the events and to test various possible scenarios and responses, which will be discussed below.
At the time of this writing the web-based ARRT is hosted on a Linux server inside the NASA JSC firewall, utilizing libraries such as dygraphs, PHP, JavaScript, Bootstrap, jQuery, HTML, and CSS. The simulated HERA dose rates for Artemis II configuration are stored locally with ARRT. It is assumed the Artemis I shielding configuration is the same as Artemis II but with only three onboard dosimeters. The functions of reading and plotting of historical HERA data are conducted through interactive calls between codes developed in PHP, JavaScript, and dygraphs. Figure 4 shows a snapshot how these interactions are performed, which is further illustrated in section 3.5. After an event is selected in the SPE list, the onset time of the input panel is automatically set as the time 72 hr before the default onset of this event, and the HERA readings of the whole span of the event are plotted in the plot panel “HERA Reading II”. In the meantime, the 7-day readings before the end of the event are plotted in “HERA Reading I”. The default values for “Factors,” “Dosimeters,” “Time Window,” “Stream Speed,” and “Refresh Frequency” are shown in Figure 4, which can be modified by the user. Dosimeters 1, 2, 3, 4, 5, and 6 refer to HPU1, HPU2, HSU1, HSU2, HSU3, and HSU4, respectively. If one or more dosimeters malfunction, the user can delete the unit(s) and their readings will disappear from the plots.

After the user clicks the “Start HERA Readings” button, both plots update at a pace set by the “Refresh Freq.” If the value of “Refresh Freq” is modified, the plotting will pause and need the user to click the “Resume HERA Readings” button to resume. If the value of “Time Window” is modified, the change will reflect in “HERA Reading II” in just one step, after that the value returns to the default 72 hr automatically. These two features were implemented to ease the usage for SRAG operations. All other modification of input values can be reflected and retained in the plots automatically. These functions are not needed for real-time operational monitoring, as the time, factor, and the dosimeters are all set in such a situation. However, ARRT can be used as an analysis tool for events just passed, such as the example illustrated in section 3.2, showing how these functions can be utilized. Additionally, the dygraphs library used in plotting allows zooming in the plots either horizontally or vertically, which is useful to examine the details of the measurement. At the bottom of each plot, there are two links for downloading data file and displaying data in a new tab, once the plot is activated.

In addition to the SEPEM data set, ARRT uses a real-time data set by linking with the databases of International Space Station (ISS) instruments maintained by SRAG, which include dose rates measured by Radiation Assessment Detector (RAD), Tissue Equivalent Proportional Counter (TEPC), and Extra-Vehicle Charged Particle Directional Spectrometer (EV-CPDS). The dose rates in the record uniformly populate ARRT from their starting service time to the present time, with a 1-min cadence. If the user selects the “RealTime” option as shown in Figure 5 and clicks “Start HERA Readings” button right after, the ISS data set will be streamed and plotted in real time, updated every minute. As the ISS instrument data are downlinked to a SRAG internal database, from which ARRT retrieves the data, the streaming can be disrupted for various reasons. When this happens, ARRT automatically sets the readings of the units as the

![Figure 4. ARRT user input panel and HERA dose rate reading and plotting for historical SPEs.](image-url)
last available dose rates until the connection is restored. Figure 5 shows two such incidents between 6 and 8 August 2019. As SRAG will maintain active instrumentation data for the future Artemis I and Artemis II missions in a similar manner as for ISS, the real-time onboard data set can be easily migrated in ARRT.

The real time data in Figure 5 are significantly different from the simulated historical data in Figure 4, because the radiation environments are different for current ISS and the GOES satellites. The ISS cruises mostly inside the Earth’s magnetosphere, with an average altitude of about 410 km; therefore, the majority of radiation sources from GCR and solar energetic particles are effectively sheltered, especially for those with low kinetic energies. However, the strength of the magnetic field is not the same along the trajectory; therefore, the measured dose rates have large oscillations. In addition, the ISS passes through the South Atlantic Anomaly (SAA) region several times every day, causing significant dose rate elevation for 5–10 min each time (Figure 5). For the GOES satellites, because they orbit above the Earth at geosynchronous altitude (≈6.6 Earth radii, about 35,786 km), their geomagnetic effects are very minor, and SAA has no impact. The planned trajectory of Artemis I will have the vehicle orbiting the Earth and traveling through the van Allen belts before flying in free space to the moon. The vehicle will then orbit the Moon and return to Earth, passing through the free space environment and the trapped radiation belts before landing. For the following Artemis II and other human exploration mission with destinations beyond LEO, the spacecraft would have a brief transit through the van Allen belts, mainly experiencing radiation environment in interplanetary space. Therefore, the HERA readings of ARRT for future missions should be more similar to the simulated historical data, without the oscillations and “spikes” as in Figure 5.

### 3.2. Detecting the Onset and End of an Event

Traditionally, the onset and end of an SPE are defined as the first and last time points of a period with continually elevated proton fluxes higher than a threshold (Feynman et al., 1990; Jiggens et al., 2012). However, because of the modulation of solar cycles, the background fluxes change significantly from the solar minimum to the solar maximum (Figure 6, left panel), and the difference of intravehicular dose rates can be as large as two to three times (Figure 3 in Norbury et al., 2019). If a fixed dose rate were chosen as the threshold to determine the onset and end of an event, the first and last time points of a same event (such as the one in Figure 6 [right panel]) would be different if it occurred at different times in solar cycles. To avoid this problem, ARRT uses the background dose rates as references for the threshold of an event, which are not fixed but varying along solar cycles.

To automatically calculate the background dose rates is not always straightforward, especially for the time period when multiple events occur sequentially. For the events plotted in Figure 6 (right panel), the
background dose rate for the first event (with onset on 7 March) is easy to calculate, as any time window of any length before the onset can be selected, and the mean dose rate is the correct background. However, for the second event (with onset on 14 March), the time window cannot be selected between 7 and 14 March, as the dose rates in this time period are elevated by the first event. In ARRT, an algorithm is developed such that a 1-week window is selected to calculate mean dose rate and the number of points below the mean. If the number of points with dose rates below the mean is less than 55% of the total number of points in this time window, it is certain that there are no SPEs during this window and the calculated mean is the background dose rate. Otherwise, the time window shifts 1 week or additional weeks behind until the condition is satisfied. This algorithm has been tested for SEPEM-generated HERA readings, and the calculated backgrounds are stable and independent from the occurrence of SPEs.

For the historical data set, the threshold for SPEs is defined as two times the background dose rate, and the onset of an event is defined as a time point with two consequential dose rates above the threshold. Currently, for the real-time SPE, the definition of onset is the same, but the threshold has to be defined as 200 times the background, because a lower threshold would misinterpret the dose rate elevation when ISS passes SAA as an SPE (Figure 5). As ISS travels inside the Earth’s magnetosphere and no significant SPE has been recorded to date, we developed code to simulate a simple event with specific starting time, hours to the peak, hours to the end, and a factor that times the original data. With these virtual events, ARRT can check if the real-time data work for the organ dose fitting module and acute risk modeling module. Figure 7 shows such an event.
starting at 15 April 2019, 00:00, with 1 hr to the peak, 240 hr to the end, and 500 times of the original readings at the flux peak. Because the code modifies the readings with a simple linear rising from background to peak and the threshold is defined as 200 times of the background, the detected onset of this event is 15 April 2019, 00:28, as shown in Figure 7. Before the onset, the “SPE Status” is in a “Nominal” mode with a green light. When the data reading reaches the onset, ARRT enters an “Event in Progress” mode with a red light in “SPE Status” (Figure 7), the time value in the “Onset” box becomes fixed, and the “Time Window” value keeps increasing at a pace set by the “Stream Speed” and “Refresh Freq.” In the meantime, the plot in “HERA Reading II” shifts its origin to the onset, displaying the readings sequentially since onset, while the plot in “HERA Reading I” continues streaming with time for 1 week’s readings. This “Event in Progress” mode works similarly for the 159 recorded SPEs in historical data set but with different thresholds. As reported by other researchers (Feynman et al., 1990; Tylka et al., 1997; Jiggens et al., 2012), many consecutive events are not independent in time, and a minimum dwelling time parameter (e.g., 24 hr in Jiggens et al., 2012) is needed so that they could be treated as the same event. Based on SRAG’s operational guidance, ARRT chooses a 2 hr dwelling time to determine if consecutive events can be treated as different events, and the end of an event is defined as a time point following 2 hr of dose rates below the threshold, for both the historical and real-time data sets. When the end is reached, ARRT goes back to “Nominal” mode with a green light in “SPE Status,” the time value in the “Onset” box changes to an unfixed onset, and the “Time Window” value returns to the default 72 hr, accompanying with the changes in the plots in nominal mode. As all effects of the previous event is reset once it reaches the end, there is a health risk issue if the event is big enough to induce ARS. To remedy this problem, a dose-dependent monitoring time parameter is introduced using the following formula:

\[
\text{monitoring time (hours)} = 24.0 \times \left(\frac{\text{total dose (mGy − eq)}}{50.0}\right)
\]

For events with total BFO dose >250 mGy-eq, which is the threshold of ARS induction for terrestrial radiation, the health effects will be monitored at least 5 days. For these rare large events, when the end is reached, ARRT goes to a “Crew Monitoring” mode with a yellow light in “SPE Status,” and the time values in the “Onset” box and “Time Window” box are maintained as in “Event in Progress” mode until this monitoring period finishes. In this way, the impacts of big events to the health of crew are preserved for complete analysis. An example for this treatment will be discussed below, to demonstrate how large consecutive events can be analyzed correctly.

### 3.3. Calculating and Plotting Organ Dose Quantities

Whenever an SPE is detected, a set of code is launched to project organ doses from dosimeter measurement. This is a complicated process with each step involving spectral matching in a precomputed dose database,
scaling factors fitting between the vehicle dosimeter measurement and the precomputed dose quantities of
the matched event, and linear scaling of the precomputed organ dose quantities (Mertens et al., 2018), which
is summarized in section 2.1. The output of each step of calculation includes 27 organ doses at eight locations
in MPCV (four nominal seats and four sheltered seats), for male and female astronauts, respectively
(Mertens et al., 2018). To reduce the amount of computation for this step, two input parameters are
introduced, that is, the “Gender” and the “Crew Location,” allowing the user to check some subtle
variations for different genders and locations in different runs. Figure 8 shows the output of a calculation
for a male astronaut at “Seated” Location 1 of the virtual event with onset on 15 April 2019, 00:28, which
was paused at 107.3 hr after onset. The organ dose plot includes $107.3 \times 60$ BFO dose rates and
accumulative doses since the onset of the event, as the cadence is 1 min.

As ARRT is a real-time operational tool for the exploration missions, all calculations are required to
finish along with the streaming of dosimeter reading. For the real-time data such as those showing in Figure 8,
all $107.3 \times 60$ steps of organ dose computation are required to finish within 1 min (the cadence of data
streaming). We found that this could not be done with sequential code or by breaking the code into sections
with each conducting a small number of times calculation or by parallelizing the code to use all nodes simulta-
aneously. The solution was found by running the sequential code just in the background of the Linux sys-
tem, and an unlimited number of processes are spawned to the backend cluster at a same time. The speed of
calculation in this way is the fastest among all trials. However, for longer duration events, the calculation
will cause a delay in the update of the plots, as additional time is needed to plot 1-week HERA data, to plot
HERA data since onset, to perform ARS calculation and plotting, and to generate flight notes. If this is the
case, the user can increase the “Stream Speed” and the corresponding “Refresh Freq” inputs to allow longer
gaps between reading dosimeter data, that is, by manually increasing the default cadence, so that all tasks
can be finished properly within the cadence. For historical SEP data set, such problems are not presented
as the cadence is 15 min and long enough to conduct the required computations even for the event of longest
duration. At the time of this writing, the Linux server hosting the code has only 16 CPUs. Once the code is
migrated into a production server with more CPUs, the speed limit should be lifted.

### 3.4. Triggering the ARS Biological Models

Early radiobiological studies suggested that all ARS symptoms are deterministic effects that manifest only
above a threshold (NRC, 1970). For example, the widely used RIPD software set 0.5 Gy as the threshold to
trigger two neurovascular models (Matheson et al., 1998). However, later investigations indicated the
damages to the radiosensitive systems have no threshold limit; at low dose levels, these changes may be loca-
lized or transient, and/or they may be repaired; at high dose radiation, they may be more widespread, severe
and persistent (Fliedner et al., 2001). Therefore, ARRT does not set a threshold for the incorporated ARS
models but generates results of various endpoints whenever an ESPE occurs.

For the virtual event described above, the total BFO dose is about 600 mGy-eq for a male astronaut at
“Seated” Location 1 after 107.3-hr exposure (Figure 8). Figure 9 shows various ARS effects that ARRT
projects, from the onset of the event to up to 42 days (1,000 hr) after the onset. The left plot displays ARS severity and performance prediction, updated in every step of real-time data reading (i.e., 1 min). This includes H-grade (HemoGrade), severity scale of UG (upper gastrointestinal) and FW (fatigue and weakness) symptoms, and PD (performance decrement). HemoGrade is modeled based on the changes of peripheral blood cell counts after radiation exposure (Hu, 2016). It indicates the extent of damage to hematopoiesis and the corresponding prognosis for autologous recovery, and it can be used to suggest optimal therapeutic treatment (see Table 1). UG and FW symptoms are outputs of two neurovascular models adapted from the RIPD models (Matheson et al., 1998), describing severity of nausea and vomiting, fatigue, and weakness in numerical scales (Table 2). Performance is defined as the baseline time for a healthy crew to complete a task divided by the time taken to complete the task when ill. Calculation of PD is based both on the severity of symptoms and the mental/physical difficulty of the crew’s assigned tasks. A PD greater than 0.75 is considered “Effective,” 0.25 to 0.75 is “Performance Degraded” and below 0.25 is “Ineffective” (Matheson et al., 1998). For the virtual event at around 107.3 hr since onset, the HemoGrade steadily increases from 0 to 1 during the first week, stays at Level 1 for the second week, then increases to peak at 1.5 and decreases to 1 during the third and fourth weeks, and maintains at Level 1 till the 42 days (Figure 9), indicating mild to moderate injury to the hematopoietic system with certain autologous recovery (Table 1). The FW score increases to 1.5 for the first week after onset and maintains at the level till 42 days, while UG and performance results show minimal or no impact at this level of exposure (Figure 9 and Table 2).

The right plot in Figure 9 describes the modeled dynamics of various blood cell counts at this scenario, which are expressed as ratios to their baseline counts. These are generated by the four hematopoietic models used in the HemoDose software (Hu et al., 2015). In addition to the counts of lymphocytes, granulocytes, leukocytes, and platelets from the onset to the 42 days, the time course of the number of hematopoietic stem cells is also reported as one endpoint of the models (Hu et al., 2012), which is an indicator of the possible autologous recovery of this system (Fliedner et al., 2002). All these outputs are updated at each step of dosimeter data reading (i.e., 1 min), along with the calculation of ARS severity scale and performance, giving updated information of the possible health outcomes of the crew and providing instant guidelines to the ground FCT. However, it is not certain if a hematological analyzer will be onboard in future exploration missions. If such a device is available, the cell counts in peripheral blood can be used to verify the projected dose as the

| Table 1 | Textual Descriptions of the HemoGrade Severity Level and Prognosis and Therapeutic Options |
|---|---|---|
| Grading | Extent of impairment | Prognosis | Therapeutic options |
| H0 | No damage | No observable symptoms | No need for hematopoietic treatment |
| H1 | Mild damage | Autologous recovery certain without critical phase | No need for hematopoietic treatment |
| H2 | Moderate damage | Autologous recovery certain with low risk critical phase | Blood component therapy if indicated by bleeding or appropriate antibiotic agents to cope with bacterial infections |
| H3 | Severe damage | Autologous recovery certain with high-risk critical phase | Same as those in H2. Additional cytokines/growth factors should be administered as early as possible |
| H4 | Fatal damage | Autologous recovery most unlikely | Stem cell transplantation, supplemented by all other supportive hematopoietic treatment |

*aCritical phase is defined as the duration with constant cell counts below the normal range, resulting high or low risks of developing bleeding or infectious diseases

| Table 2 | Textual Descriptions of the Symptom Severity Level of Prodromal Radiation Sickness |
|---|---|---|
| Severity level | Nausea/vomiting | Fatigue/weakness |
| 1 | No effect | No effect |
| 2 | Upset stomach, clammy and sweaty, mouth waters | Somewhat tired, with mild weakness |
| 3 | Nauseated, considerable sweating, swallows frequently to avoid vomiting | Tired, with moderate weakness |
| 4 | Vomited once or twice, nauseated, and may vomit again | Very tired and weak |
| 5 | Vomited several times, including the dry heaves, severely nauseated, and will soon vomit again | Exhausted, with almost no strength |
HemoDose tool does (Hu et al., 2015). In addition, they can serve as real-time biomarkers to assess ARS and develop clinical guidelines. An additional merit of the plots in Figure 9 is the projection of the critical phase, which is defined as the duration with constant cell counts below the normal range, resulting high or low risks of developing bleeding or infectious diseases. For the virtual event, the calculation indicates that such phase may appear during the third and fourth weeks after the onset, giving plenty of time for the ground FCT to make decision if any medical intervention as listed in Table 1 is needed (Hu, 2016). Because SPEs can be effectively shielded, and current vehicle designs incorporate smart shielding concepts such as the redistribution of vehicle mass in MPCV, with an effective warning system for a large SPE to reduce the event exposure, it is very unlikely that astronauts inside an interplanetary spacecraft like MPCV will experience such severe health impacts that need these medical interventions (Hu et al., 2020).

3.5. Generating a Flight Note for ARS Management

As described above, MPCV is designed with an integrated shelter. If there is a possible risk to crew health, the crew will be asked to perform the Radiation Event Cabin Reconfiguration (RECR) protocol and seek shelter in the storage bays. Generally, crew shelter can be assembled in 30 min, and the crew can safely remain in the shelter through the event, leaving briefly as approved to conduct mission critical or hygiene-related tasks. As one of the console operators’ suite of tools, ARRT will be initiated at launch and run consistently in the background. Once an ESPE is detected, ARRT will notify the radiation console team automatically and perform ARS projections. This information will be used to automatically generate a Flight Note for communication with FCT, who make all recommendations through the Flight Surgeon.

Figure 10 displays a sample flight note for a male astronaut if encountering a virtual event depicted in Figures 6 and 7. The note contains information on space weather conditions, recommended crew actions, short-term crew impacts (48 hr), and continuing crew impacts (2 days to 6 weeks). Except for the space weather conditions, all crew actions and impacts are generated automatically by ARRT.

| Space Weather Conditions: |
|---------------------------|
| An ESPE was observed at 2019-04-15 00:26:00 as defined by [Flight Rule]. The mission average background dose, as monitored by HERA, is 7.10E-3 mGy/hr. As of 2019-04-19 11:46:00, the average dose rate is 3.93E-0 mGy/hr. |

| Recommended Crew Actions: |
|---------------------------|
| Based on the projected short-term crew impacts (see below) the crew is recommended to perform the Radiation Event Cabin Reconfiguration protocol and seek shelter in the storage bays per [Flight Rule]. |

| Short-Term Crew Impacts (48 hours): |
|-------------------------------------|
| On-board instrumentation indicates that as of 2019-04-19 11:46:00, total exposure due to this ESPE was 6.96E+2 mGy. According to model predictions, a total bone marrow exposure of 6.27E+2 mGy-req is projected. At this level, per [Flight Rule], Acute Radiation Syndrome is a concern for the crew. Symptoms such as nausea and anorexia may appear within 24 hours of exposure, manifested as an upset stomach with clammy/sweaty skin and watering mouth. Complete disappearance of these symptoms is certain within 48 hours of exposure. Fatigue and mild weakness may appear during this time period. Bloodwork will indicate a mostly asymptomatic decrease in lymphocyte concentration. |

The following crew impacts are expected over the next 48 hours since the onset of the ESPE*:

| Symptom           | 2h | 4h | 6h | 12h | 18h | 24h | 36h | 48h | Incidence (%95CI) |
|-------------------|----|----|----|-----|-----|-----|-----|-----|------------------|
| Nausea/Vomiting   | 0.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.0 (4.47.0.06) |
| Fatigue/Weakness  | 0.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.0 (4.17.1.00) |
| Performance Decrease | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | N/A |
| HemoGrade         | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | N/A |

*Check the reference tables for the definitions of the symptom severity levels, incidence, performance decrement, and HemoGrade.

Continuing Crew Impacts (2 days - 6 weeks):

Fatigue and weakness may persist for several weeks. The crew are at low risk of developing infectious diseases or bleeding due to a decrease in concentrations of lymphocytes, platelets, and granulocytes below the lower end of the normal range. Autologous recovery is certain.

Figure 10. Flight note for a male astronaut if encountering a virtual event depicted in Figures 6 and 7.
weather conditions, all other information is generated based on the results of ARS modeling calculation. The thresholds to recommend crew action and ARS concerns are both set as 100 mGy-eq, and that for short-term crew impacts is set as 250 mGy-eq. The texts of symptoms description and recommendation are categorized into eight scenarios based on the calculated total BFO dose from the organ dose estimation code (supporting information), which can be changed as the ESPE progresses in time. The table listed in flight note gives numerical scores for NV, FW, PD, and H-grade over the first 48 hr since onset, as well as incidence of the two neurovascular effects. Like the ARS plots, all texts in flight note are updated at every time step of dosimeter reading and can be downloaded in Microsoft Word format. If no increase in dose over threshold, only space weather conditions will appear in flight note, with mission background dose rate and the average dose rate of the present time, and the note download link is inactive.

3.6. Software Structure of ARRT

ARRT was developed with many state-of-the-art facilities for full stack web development, with its overall workflow depicted in Figure 11. The user interacts with an interface to set parameters of the query (i.e., time window and stream speed). Then the application loads the appropriate data set, processes the data to check if ESPE threshold is reached, in the meantime to visualize the data and to generate flight note. Certain levels of ESPE result in additional calculations, expanded visualizations, and detailed flight notes, all of which happen seamlessly by modifying SPE status and input parameters automatically (Figure 11). Regardless of the existence of an ESPE, the modules run corporately and execute continuously, unless the user clicks the “Pause HERA Readings” button (Figures 4 and 6). After the pause, the user can click the “Resume HERA Readings” button, and all processes resume and catch with the real-time stamp (for historical data set, they continue from the time point paused).

4. ARRT Operation for a Typical Event

The occurrence of ESPEs is hard to predict, and their developing patterns are vastly different. Table 3 lists 20 biggest events occurred between 1974 and 2015, calculated from SEPEM 2.0 data set (http://www.sepem.eu/). It is clear that every event is unique, in terms of total dose, dose rate at peak, duration, as well as the waiting time. Additionally, the time for dose rates to reach the peaks and the time parameters for accumulative doses can be different as large as over two magnitudes. To be able to process the diverse features of the events, the ARRT code should be flexible enough to deal with different scenarios, but in the meantime be robust to generate the correct results in an automatic manner. Additional challenges exist for multiple events occurring in a short time period. To make the outcome of ARS prediction more relevant for the console operational team, it is not always easy to decide whether to treat sequential events separately or interdependently. The robustness of ARRT has been tested with all the simulated HERA readings from SEPEM 2.0 data set, and for all of the 159 significant events, ARRT can correctly read and plot the data, project organ doses and ARS risks, and generate flight notes consistent with numerical results. In the following an event with multiple subevents is used to demonstrate how ARRT is smart to treat sequential events correctly.

The 2003 Halloween storm is a typical ESPE with multiple events lasting for more than 10 days, which ranks No. 4 among the biggest events during 1974–2015 (Table 3). The proton fluxes recorded by GOES detectors indicate five subevents nearly overlapping with each other (Figure 12; Mertens et al., 2010), whose onset and end times are listed in Table 4 according to different definitions. The NOAA parameters are estimated by using the proton data archived at NOAA’s National Center for Environmental Information (http://www.ngdc.noaa.gov/stp/satellite/goes/index.html), which defines the start of an SPE as when the >10-MeV integral proton flux exceeds 10 proton flux units (pfu ≡ cm⁻²sr⁻¹s⁻¹) in three consecutive 5-min periods and the end as the last time the flux was greater than or equal to 10 pfu. As the fluxes of >10-MeV protons between
Events 2 and 3 are not below the threshold (Figure 12), they should be considered as one event by this definition. As discussed above, ARRT’s definition is based on the elevation of HERA dose rates within the MPCV. Because the contribution to silicon dose behind the spacecraft shielding comes mainly from protons in energy range 100–300 MeV (Figure 3), the onset and end times estimated by ARRT are substantially different from NOAA’s. The dwelling time between Events 2–3 and Event 4 is about 24 hr with NOAA’s definition but increases to 58.5 hr with ARRT’s definition (Table 4).

If the factor of ARRT run is 1, that is, no enhancement applied to the original data, treating these events separately causes no issues for health risk analysis, as the BFO doses for these four events are 0.08, 15.5,
1.25, and 0.11 mGy-eq, respectively, all far below the threshold to trigger ARS response (i.e., 250 mGy-eq). However, if a factor of 20 is applied (for postevent analysis), the Events 2–3 will generate a BFO dose of 310 mGy-eq for astronauts inside MPCV, which will induce ARS that may last 4–6 weeks (Figure 9). As Events 4 and 5 will add significant doses and deteriorate the ARS in this scenario, they should be included in risk estimation together with Events 2–3. There are different ways to include subevents in an episode (Robinson et al., 2018). One simple way is to extend the dwelling time if an event reaches the threshold, and the length of the dwelling time depends on the size (i.e., dose) of the event, which is how ARRT adapts. This dose-dependent dwelling time is better than one with a fixed length, as the dwelling time (waiting time) varies significantly for different events (Table 3). Applying the threshold is important in the algorithm, as otherwise any event will lead the tool into a “Crew Monitoring” mode for a certain time, which is unnecessary for small events that are of no concern for certain. The quantitative relationship of the dose dependence is also essential, which needs to extend the dwelling time to the time window relevant to ARS risks for significant exposure. Furthermore, the exposure induced by the following events needs to be taken account in real time, so that the duration can be further extended when total dose of the episode increases. All these considerations have been implemented seamlessly in the code of the flight note module which detects and determines the onset and end of an event.

Figure 13 shows a snapshot of ARRT run for an event of a magnitude of 20 times the 2003 Halloween storm. In this scenario the total BFO dose for Event 1 is 1.6 mGy-eq, and it is treated as an independent event. The onset of Event 2 is the same as the original data, as the background dose rates are elevated with a same factor. As the BFO dose gradually increases to over 100 mGy-eq and then over 250 mGy-eq, the flight note content

![Figure 12. GOES-11 proton flux measurement of 26 October 2003 ESPE (top, adapted from Mertens et al., 2010) and ARRT simulated HERA readings (bottom).](image)

### Table 4

| Subevents | NOAA onset | NOAA end | ARRT(1)a onset | ARRT(1)a end | ARRT(20)b onset | ARRT(20)b end |
|-----------|------------|----------|----------------|--------------|----------------|--------------|
| 1         | 10-26, 18:35 | 10-27, 19:40 | 10-26, 18:10 | 10-26, 10:25 | 10-26, 18:10 | 10-27, 10:25 |
| 2–3       | 10-28, 12:25 | 11-01, 10:50 | 10-28, 11:40 | 10-31, 07:10 | 10-28, 11:40 | —            |
| 4         | 11-02, 11:05 | 11-04, 19:40 | 11-02, 17:40 | 11-04, 10:25 | —              | —            |
| 5         | 11-04, 22:35 | 11-07, 12:25 | 11-05, 00:10 | 11-05, 17:55 | —              | 11-12, 18:55 |

Dates are formatted as MM-DD.  
\(^a\)The factor of ARRT run is 1.  
\(^b\)The factor for ARRT run is 20.
for “Recommended Crew Actions”, “Short-term Crew Impacts”, and “Continuing Crew Impacts” changes
texts according to the response categories described in supporting information, and other contents as well
as the table for the first 48 hr crew impacts are updated at each time step. After Events 2–3 initially stop
at 31 October 2003, 7:10, the “SPE Status” changes to “Event completed, Crew Monitoring” (yellow light
on). Because the total BFO dose at this stage is 310 mGy-eq, the initial dwelling time is 6.2 days (i.e., 310/50,
according to the definition), so the system continues to read on data, do all kinds of calculation, and update
the flight note and ARS response at every time step. If there were no following events, this monitoring
mode would continue till 6 November 2003, 12:00, that is, the end of the event according to the definition
of ARRT.

Because Event 4 occurred on 4 November 2003, 10:25, which is before the end initially determined by the
total dose of Events 2–3, the dwelling time set by Events 2–3 is redefined according to the algorithm.
When Events 4 and 5 kick in, they not only add the total BFO dose but also nullify the count for time points
below the dose rate threshold. Because the dwelling time is determined by the time points below the thresh-
old, it is refreshed during the periods of Events 4 and 5. As the total BFO dose at the end of Event 5 is around
337 mGy-eq, the updated dwelling time becomes 6.74 days at this stage. That is why the end of the Events 2–5
(one episode) goes to 12 November 2003, 18:55 (Table 4), far later than the initially determined end
time. Such a long time of crew monitoring phase is quite reasonable as the critical phase of ARS is usually
3–4 weeks after significant exposure (Hu, 2016). From the plots of ARS severity and blood cell dynamics
in Figure 12, the monitoring phase covers one third of the ARS projection, giving sufficient time for ground
mission control team to estimate possible health effects during the following critical phase. However, for
such severe events, it is more crucial not to wait till this stage but to apply methods of forecasting the dose
buildup over time from the measurement at very early time of the event, so that crews can take prompt
action to mitigate the effects by entering a shielded area designed for their protection (Lovelace et al., 2018).

5. Conclusions and Further Works

The health risks of space radiation present the most serious challenges to space exploration, and the unpre-
dictable ESPEs add significant radiation dose to astronauts in a short period of time, while rare large events
can induce ARS requiring close crew monitoring and management even during the missions. ARRT was developed to directly use the readings of onboard dosimeters to project organ doses for the upcoming space explorations, so that any possible ARS risks to the astronauts can be modeled and monitored in real time, removing dependence on the measurements by other instruments that may not be able to detect ESPEs along the trajectories of the spacecrafts. This operational tool represents a good example of effort to transition research to operation, as many years of works in space radiation measurement and modeling, transport calculation for high-energy particles, and acute radiation responses for human are involved and elegantly implemented in this compact software to be tested and utilized operationally in the upcoming Artemis missions.

To enable ARRT to handle variant scenarios of any possible ESPEs in an automatic manner for mission operation, two data sets were employed in developing its modules, one involving historical solar protons recorded over the past four decades and the other using the real-time telemetric readings of dosimeters onboard ISS. Though vastly different in terms of data cadence, smoothness, and bad data gaps, all events in these data sets can be correctly processed to read and plot, to project organ doses and ARS risks, and to generate flight notes relevant to the console operational team. All these tasks are completed with close interactions between multiple modules developed with many state-of-the-art facilities of full stack web applications. As an ESPE may last days or even weeks, and all data processing, dose projection, graphic presentation, and text updates need to be performed in real-time, the computation resource for this tool is very demanding. Thanks to the fast developing computational techniques such as concurrent data structures, parallel algorithms, and multithread management, as well as product scalability of cloud computing platforms, which are employed in the developing process, this tool meets the requirement to project radiation exposure and to provide clinical guidelines in very short time steps even for the longest event in data sets. All these efforts make this tool eligible to be tested the upcoming Artemis missions.

To be properly used in future space exploration such as Mars missions, many other factors must be carefully considered in ARRT. For example, the two-way light travel time could be as much as 25 min to Mars, so even all telemetry connection and streaming processes are in perfect condition, the data ARRT receives are impossible to be in real time. In addition, if a severe ESPE occurs and hits the spacecraft, not only are the onboard electronics greatly impacted (Xapsos, 2019), but also the interplanetary media and magnetic field would be dramatically modified (Desai & Giacalone, 2016). All these will significantly increase the challenges of proper signal transmission between the vehicle and ground support team. It will be more practical to enlist ARRT as an onboard tool for these long-distance missions and to make it simpler and more intuitive for the crew to operate and monitor by themselves. In fact, the current version of ARRT can run in background automatically for weeks even months, as long as the user does not want to pause it or refresh it. Another direction of improvement is to link it with ESPE forecasting and/or nowcasting tools (Anastasiadis et al., 2019; Lovelace et al., 2018) and probabilistic models with user-specified mission and confidence level (Robinson et al., 2020), so that the crew and the ground support team can be well prepared before such events occur. Yet since the crewed Artemis missions are currently scheduled to launch close to the maximum of Solar Cycle 25, ARRT will be particularly useful for crew to take (emergency) precautionary measures during these upcoming missions.

**Data Availability Statement**

The material and shielding thicknesses files of MPCV were determined by ray tracing the CAD model by Hatem Nounu. Figure 1 was obtained from internal report, and the left panel of Figure 6 was generated by Kathryn Whitman from SEPEM data set. Solar proton data and software used can be found online (SEPEM: http://sepem.eu/help/data_ref.html; Software: dygraphs: http://dygraphs.com/). Because AART is a mission operational tool, ARRT can be accessed only within the NASA JSC firewall.

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