Activity II: Modeling Radiation-Damaged DNA

In Activity II, students will use candy (or Styrofoam balls) to construct a model of deoxyribonucleic acid (DNA) and will then alter the model to visualize what happens to DNA when it is damaged by radiation.

You can customize this activity by instructing the students to either: (1) Construct a DNA model by first building individual nucleotides, and then assembling the double-stranded DNA molecule (page 4; this more accurately represents the natural biochemical process of DNA assembly), or (2) Construct the entire DNA model exactly as shown in the activity (page 5).

Background

DNA is the blueprint of life stored in the cells of every organism. A DNA molecule has the shape of a double helix ladder that is only ≈2 nm wide. DNA is made of individual units called nucleotides. Each nucleotide has two parts – a phosphate-sugar part that forms part of the backbone, or strand, and the base that is the information for the sequence, or, genetic code. The backbone strands of the helix are made of alternating phosphate and ribose sugar molecules. The bases match up along the center of the ladder to join the two strands together. The base pairs form the "rungs" of the DNA ladder. There are just four different types of bases in DNA: adenine, thymine, guanine, and cytosine. Figure 13 shows computer-generated molecular models of normal DNA, and DNA that is experiencing damage due to incoming radiation. Breaks in the two strands that form the backbone of DNA are among the most difficult for cells to repair. Radiation can sever one or both strands of the molecule, forming single or double strand breaks. Figure 14 is a diagram showing the difference between the two forms of damage on an DNA molecule. In this activity, students will start by building 4-base-pair models of a DNA molecule, and then they will join together in groups of four to combine the 4-base-pair models together and create a 16-base-pair DNA model. Refer to Modules 1 and 2 for background information about radiation and biological effects of radiation exposure.

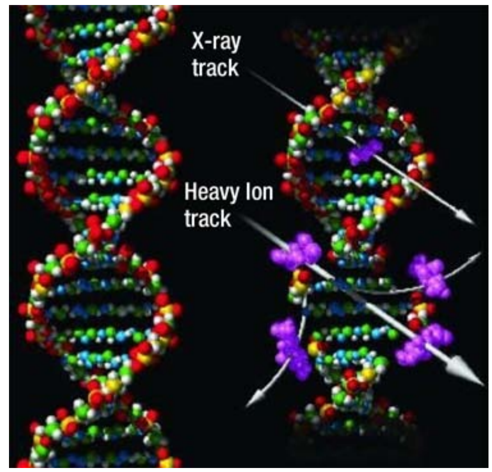


Figure 13: Molecular model depicting normal DNA (left) and radiation damaged DNA (right). Image Credit: NASA

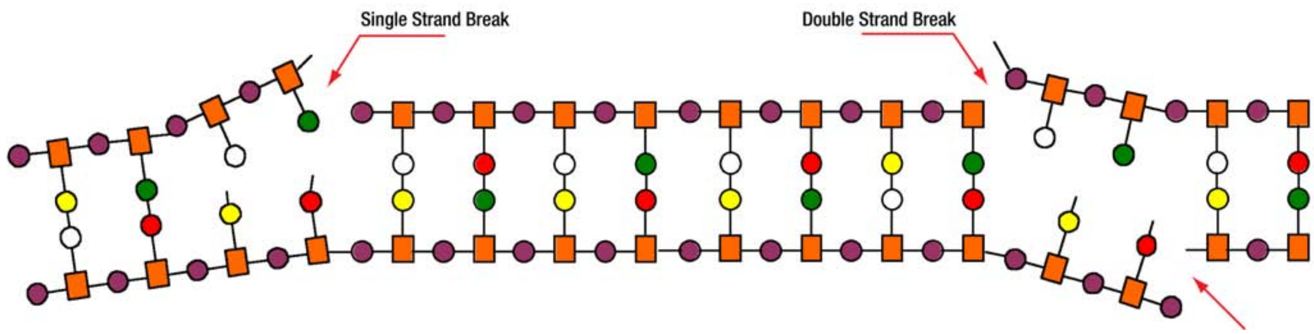


Figure 14. DNA model with two examples of DNA damage shown. The parallel linked sequences of orange squares (□) and purple circles (○) represent the phosphate(○)-deoxyribose sugar (□) strands, or backbone, of a DNA molecule. The pairs of circles linking the two strands represent nucleotide base pairs. In the single strand break, note that although some nucleotide base pairs have been separated, only one strand of the two DNA strands has been broken (indicated by red arrow). In the more severely damaged double strand break example, nucleotide pairs have been split apart and both strands of the DNA molecule are broken (indicated by red arrows).

Objectives:

By the end of this lesson, the students will be able to:

- Construct a model of a DNA molecule.
- Understand that DNA can be damaged from radiation.
- Visualize models of different kinds of radiation-damaged DNA.
- Explain the difference between double strand and single strand breaks.

Research Question:

Why is a double strand break in DNA more damaging than a single strand break?

Discussion Questions:

For planning a human-tended lunar outpost, have students discuss in detail how the presence of space radiation will affect the design of habitats for humans and other living organisms (such as crops grown for food). Other possible topics for discussion include:

- How many strands make up DNA?
- What does DNA do?
- What is a single strand break?
- What is a double strand break?
- Can DNA function when it is broken?
- What do the toothpicks in this activity represent?
- What kinds of radiation can damage DNA?

National Education Standards[35]:

Unifying Concepts and Processes

  Systems, order and organization

  Evidence, models, and explanation

Science in Personal and Social Perspectives

  Natural hazards

  Personal health

35 National Science Education Standards, Center for Science, Mathematics, and Engineering Education (CSMEE), National Academy of Sciences, National Academy Press, Washington, DC., 1996, ISBN 0-309-05326-9.

Science and technology in society

Physical Science

Transfer of Energy

Earth and Space Science

Structure of the Earth system

Materials:

1. Gum drops, five colors minimum (As an alternative, marshmallows could be used).
2. Candy orange slices, (or other soft candy that is larger than gum drops).
3. Plain flat toothpicks (may be cut in half).
4. Option: One inch-diameter Styrofoam balls can be substituted for candy. The balls can be colored or labeled by the students to represent the bases, phosphates and sugars. There should be a minimum of 6 different colored items.
5. Colored pencils
6. 4 – 5 Paper towels each, or a large piece of paper, to provide working space
7. Large table (or space on floor) to place long DNA models

Provide each student with the candies (or Styrofoam balls) and toothpicks needed to construct a DNA molecule that is four base pairs in length. Define the key for your models below.

Number of candies for each DNA Model: (fill in color)

8 = (P)__________________ = Phosphate group

8 = (Sugar) ______________ = Deoxyribose sugar group

2 = (C)__________________ = Cytosine base

2 = (G)__________________ = Guanine base

2 = (T)__________________ = Thymine base

2 = (A)__________________ = Adenine base

30 = (lines) Toothpicks = chemical bonds

After each student has constructed their model, partner four students together and combine all four models to create one 16-base-pair long DNA model.

Time allotment: 60 - 120 minutes

References:

Additional three-dimensional DNA modeling can be done using kits that are available commercially from science education material suppliers.

Going Further:

For additional research opportunities, have students investigate:

- Astrobiology and Radiation (to understand the effect of radiation on the surface of Mars and implications for life on Mars).
- Beneficial uses of radiation, such as radiation therapy, nuclear imaging in medicine (CT Scans or PET Scans),
- Brachytherapy, or the use of radioactive material in smoke detectors.

Name: ___________________________ Date: ____________________

Constructing A DNA Model One Nucleotide At A Time

Directions: Use the instructions and diagrams below to help construct your model of DNA. The model that you will create will be made from eight nucleotides. The nucleotides will be assembled together to create a DNA model that is four complimentary nucleotide pairs in length - the completed model will look like a ladder. After filling in the color key to distinguish each component in the DNA model, use toothpicks to connect the candies together as shown in the diagram below. Each toothpick represents the chemical bonds that hold the building blocks of DNA together.

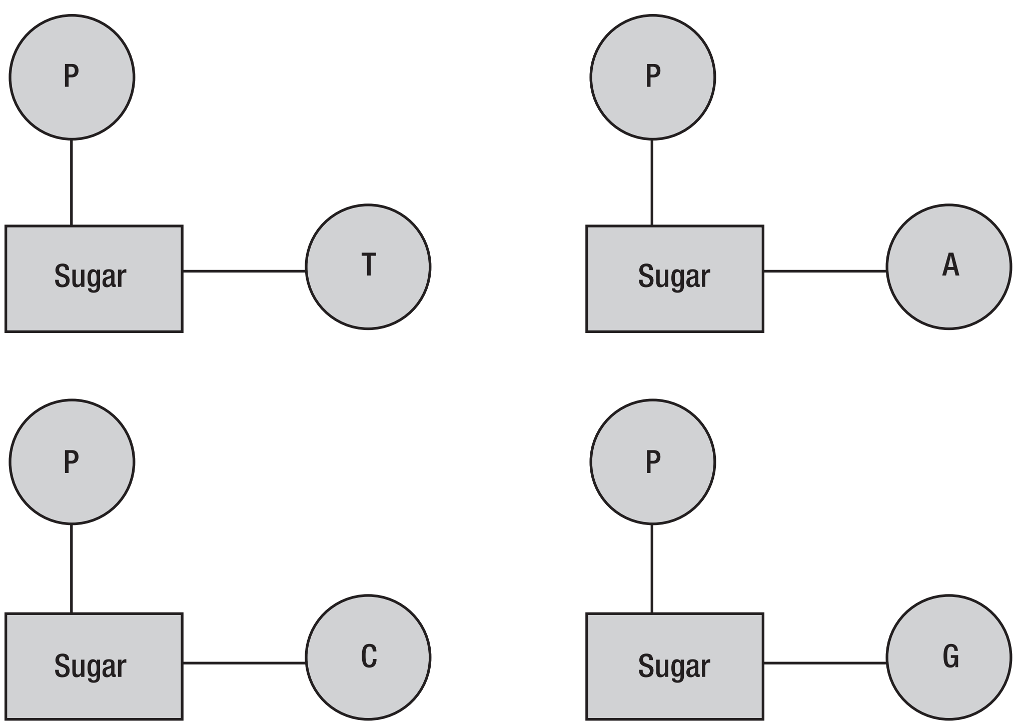
1. Working on a clean surface, group candies by color. Determine which color will represent each DNA component and fill in the key. Then color or write in the color name in the diagram below showing the P, Sugar, C, G, A, and T.

Key for DNA Model (fill color in blank):
(P) = Phosphate group = ____________________
(Sugar) = Deoxyribose sugar group = ____________
(C) = Cytosine base = ______________________
(G) = Guanine base = ______________________
(T) = Thymine base = ______________________
(A) = Adenine base = ______________________

(lines) Toothpicks = chemical bonds

2. Construct the four nucleotides as shown in the diagram below.

3. To construct the first strand of DNA, place each nucleotide laying flat on the table in front of you. Use a toothpick to connect the sugar of one nucleotide with the phosphate of another. Repeat this step until all four nucleotides are connected. When this is complete, one strand of your DNA molecule is finished.



4. Construct four more nucleotides identical to those you just constructed.

5. Connect the correct complimentary base to your first nucleotide to form the first base pairing in the DNA “ladder”. Remember: in DNA, adenine only bonds with thymine (A:T or T:A), and cytosine only bonds with guanine (C:G or G:C), and the phosphate group links the deoxyribose sugars to form the backbone. If you need help, use the diagram in the discussion sheet.

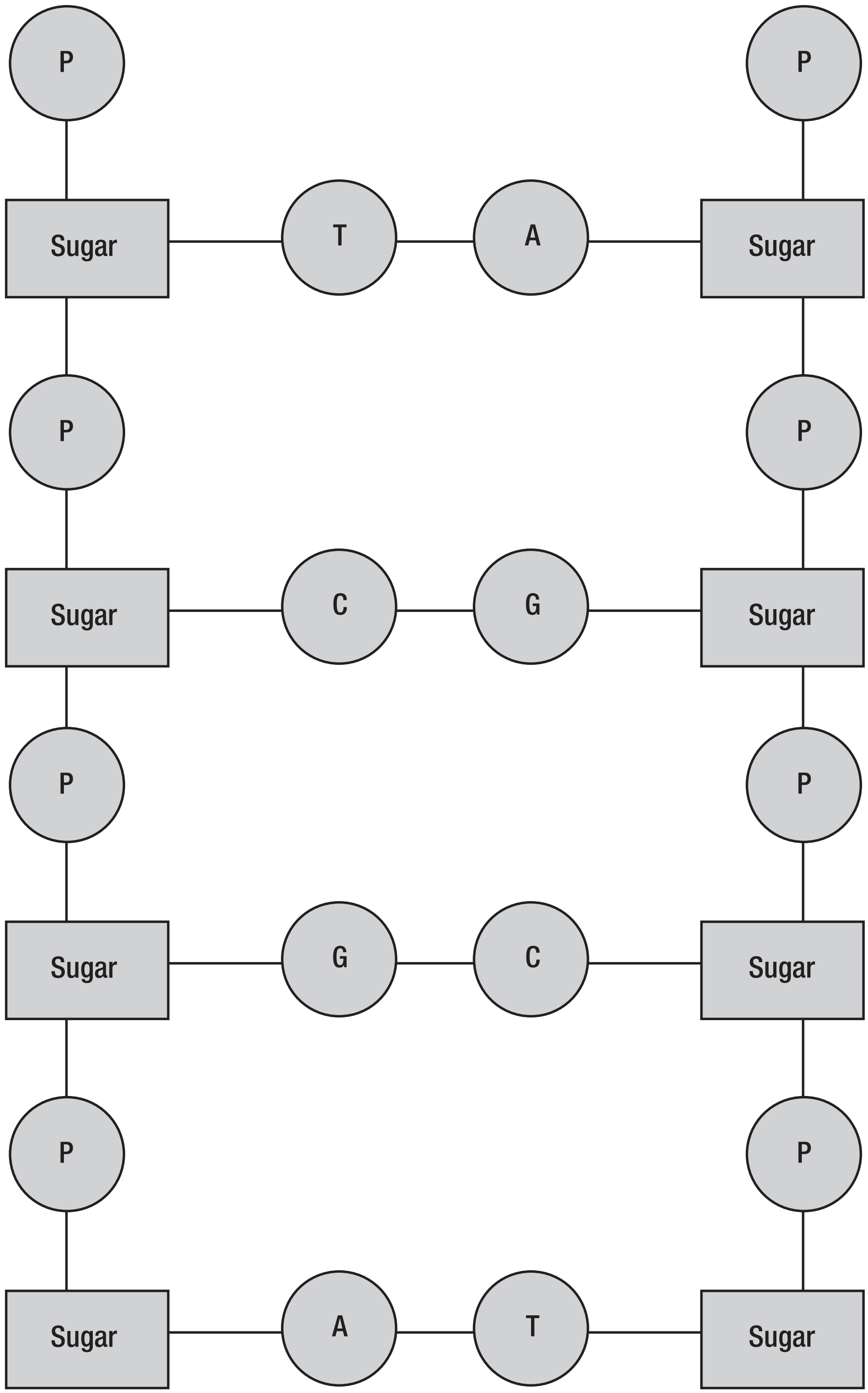
6. Continue adding the remaining nucleotides to form your DNA model. When all eight nucleotides are in place, you have completed your double-stranded model of DNA.

7. Follow the instructions and answer the questions on the “Modeling Radiation Damaged DNA Discussion Sheet.”

Name: ______________________________ **Date:**______________________

Constructing A DNA Model

Directions: Use the diagram below to help construct your model of DNA. This will vary depending upon your model components. The color key identifies each component of the DNA model. Use toothpicks to connect the candies (or Styrofoam balls) together. The toothpick connections represent the chemical bonds that hold the building blocks of the DNA molecule together. After follow the instructions and building your DNA molecule, answer the questions on the "Modeling Radiation-Damaged DNA Discussion Sheet."

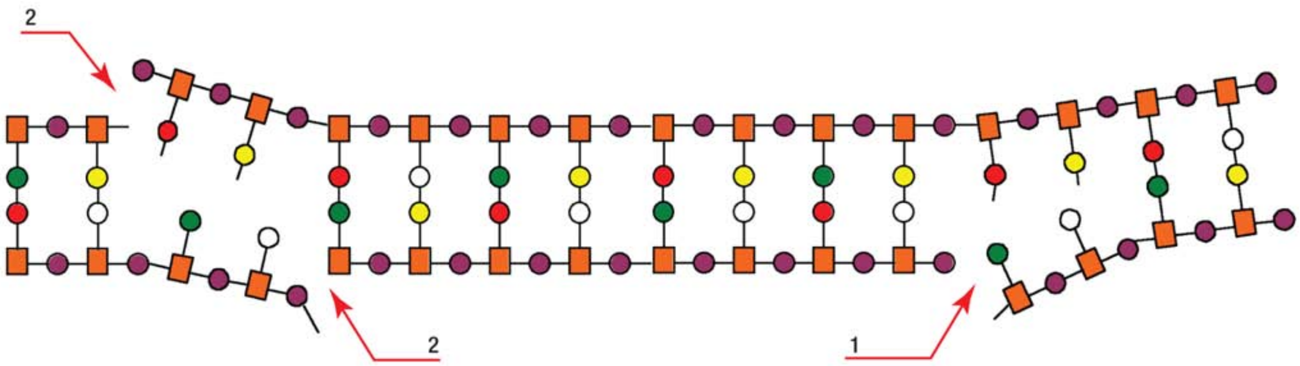


Name: ___________________________________ **Date:**_______________________

Modeling Radiation Damaged DNA Discussion Sheet

(1) How many strands of nucleotides make up DNA?

(2) Study the diagram below. Partner up with three other students and combine your models to make a longer DNA model. Imagine that your DNA molecule is being bombarded by radiation. Modify your DNA model to look similar to the break labeled "1." Answer the following questions:



How many nucleotide strands of your DNA model have been broken? _________

What do the toothpicks represent? _____________________________________

Is your DNA model in one or two pieces? ____________

Is this a single or double strand break? ______________

(3) Imagine that even more radiation bombards your DNA molecule. Modify your DNA model to look similar to the break labeled "2." Answer the following questions:

How many nucleotide strands of your DNA model have been broken? _________

Is your DNA model in one or two pieces? ____________

Is this a single or double strand break? ______________

(4) Which chemical bonds must be repaired in a double strand break to return the molecule back to its original shape?

(5) Can DNA function normally if it is broken?

(6) What effect would a few single strand breaks would have on a cell? On the body?

(7) What effect would many double strand breaks would have on a cell? On the body?

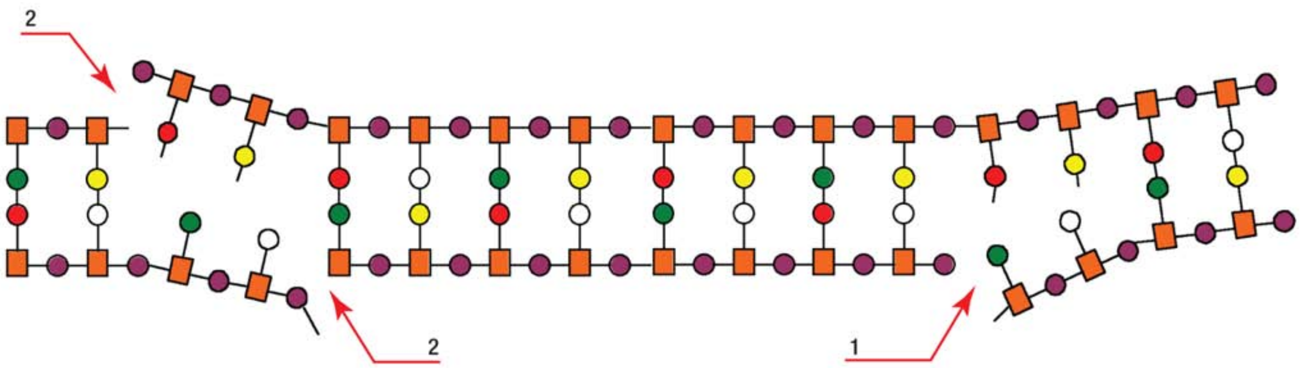
(8) What kinds of radiation can damage DNA?

Answer Key **Modeling Radiation Damaged DNA Discussion Sheet**

(1) How many strands of nucleotides make up DNA?

two

(2) Study the diagram below. Partner up with three other students and combine your models to make a longer DNA model. Imagine that your DNA molecule is being bombarded by radiation. Modify your DNA model to look similar to the break labeled "1." Answer the following questions:



How many nucleotide strands of your DNA model have been broken? one

What do the toothpicks represent? chemical bonds that hold the building blocks of the DNA molecule together

Is your DNA model in one or two pieces? one

Is this a single or double strand break? single strand break

(3) Imagine that even more radiation bombards your DNA molecule. Modify your DNA model to look similar to the break labeled "2." Answer the following questions:

How many nucleotide strands of your DNA model have been broken? two

Is your DNA model in one or two pieces? two

Is this a single or double strand break? double strand break

(4) Which chemical bonds must be repaired in a double strand break to return the molecule back to its original shape?

The bonds between the phosphates and sugars on both DNA strands, and those between the nucleotides must be repaired.

(5) Can DNA function normally if it is broken?

No, not until it is repaired.

(6) What effect would a few single strand breaks would have on a cell? On the body?

Cells with DNA containing a few sites of single stranded damage are likely to be able to repair the damage. However, some of repair may be done incorrectly. Incorrectly repaired DNA can result in mutations within the genetic code. Dependingon the region of DNA where a mutation takes place, the result may have no physiological consequence, or it may cause minor or major changes in how a cell functions. One or more mutations can reduce the ability of a cell to control cell division. If this happens, the exposed person may develop cancer. These effects may take years to decades to become apparent.

(7) What effect would many double strand breaks would have on a cell? On the body?

Many double strand breaks would badly damage DNA. This would be difficult for a cell to repair. Cells that contain DNA that is badly damaged may not be able to repair the damage, and the cells die. If this occurs in only a few cells, this is actually better for the organism, because there is then no chance of mutations resulting from faulty repair of the DNA. However, if DNA is badly damaged in many cells in a particular tissue or organ, and a large number of cells die, then that tissue or organ no longer can function properly. This can compromise the exposed person's health, within weeks, or over time, up to years.

(8) What kinds of radiation can damage DNA?

High energy, ionizing radiation such as X-rays and gamma rays, and particle radiation such as galactic cosmic radiation.

Protection from Radiation

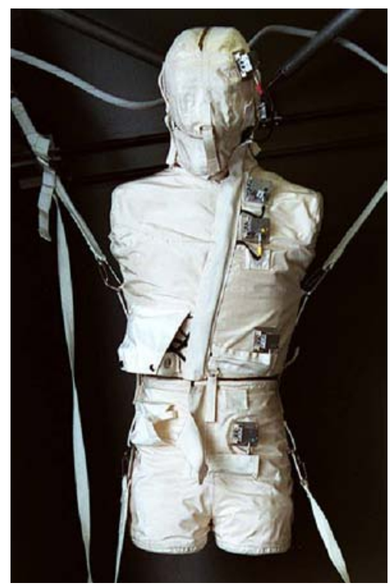
Space radiation can penetrate habitats, spacecraft, equipment, spacesuits, and can harm astronauts. Minimizing the physiological changes caused by space radiation exposure is one of the biggest challenges in keeping astronauts fit and healthy as they travel through the solar system. As mentioned previously, ionizing radiation is a serious problem that can cause damage to all parts of the body including the central nervous system, skin, gastrointestinal tract, skeletal system, and the blood forming organs. However, biological damage due to radiation can be mitigated through implementation of countermeasures that are designed to reduce radiation exposure and its effects. In this section, we will discuss the use of radiation dosimetry and operational, engineering, and dietary countermeasures.

Why is NASA Studying Radiation Countermeasures?

Radiation protection is essential for humans to live and work safely in space. To accomplish this challenging task, NASA has developed the Radiation Health Program. The goal of the program is to carry out the human exploration and development of space without exceeding acceptable risk from exposure to ionizing radiation. Legal, moral, and practical considerations require that NASA limit risks incurred by humans living and working in space to acceptable levels.[36] To determine acceptable levels of risk for astronauts, NASA follows the standard radiation protection practices recommended by the U.S. National Academy of Sciences Space Science Board and the U.S. National Council on Radiation Protection and Measurements.[37]

What is Radiation Dosimetry?

In low Earth orbit, astronauts lose the natural shielding from solar and cosmic radiation provided by the Earth's atmosphere. In deep space astronauts also lose the shielding provided by the Earth's strong magnetic field. So, to achieve the goal of the NASA Radiation Health Program, it is necessary to monitor the radiation environment inside and outside a manned spacecraft.



NASA uses an anatomical model of a human torso and head that contains more than 300 radiation sensors.

An important part of every manned mission is radiation dosimetry, which is the process of monitoring, characterizing, and quantifying the radiation environment where astronauts live and work. Radiation biology support during missions also includes: calculated estimates of crew exposure during extra-vehicular activity; evaluation of any radiation-producing equipment carried on the spacecraft; and comprehensive computer modeling of crew exposure. Space station crewmembers routinely wear physical dosimeters to measure their accumulated exposure and, post flight, provide a blood sample to measure radiation damage to chromosomes in blood cells.[38] In addition, experiments on the Space Station have been carried out using a synthetic human torso, which has over 300 strategically placed dosimeters to determine the levels of cosmic radiation absorbed by specific organs in the human body during space flight.[39] Active monitoring of space radiation levels within the Space Station is achieved with dosimeters both to identify the best-shielded locations within the Space Station and to give early warning should radiation levels increase during a mission due to solar storms.

All these sources of information are carefully analyzed before, during, and after to help mission planners mitigate the four significant radiation-related health risks that are described in the NASA Bioastronautics Critical Path Roadmap:[40] cancer, radiation damage to the central nervous system, chronic and degenerative tissue diseases, and acute radiation sickness. See the previous section for information on the biological effects of radiation.

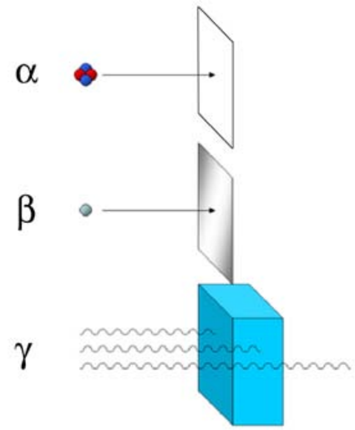
36 http://srag.jsc.nasa.gov/Index.cfm#
37 http://www.nasa.gov/audience/foreducators/postsecondary/features/F_Understanding_Space_Radiation_prt.htm
38 http://exploration.nasa.gov/programs/station/Chromosome-2.html
39 http://exploration.nasa.gov/programs/station/Torso.html
40 http://bioastroroadmap.nasa.gov/User/risk.jsp

What Are Operational Countermeasures?

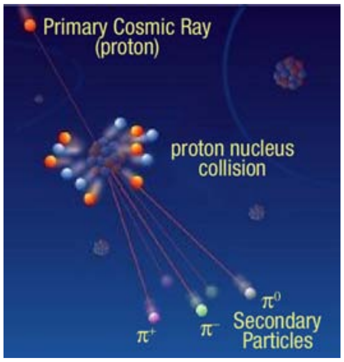
Currently, the main operational countermeasure against the adverse affects of radiation is simply limiting astronaut exposure, which means limiting the amount of time astronauts are allowed to be in space. This is accomplished primarily by shortening overall mission duration on the Space Station to 3-6 months, reducing the time astronauts spend outside of the spacecraft during spacewalks, and planning space missions during times of reduced solar storm activity. However, since future long-term missions of exploration to the Moon and beyond will both take longer (a round-trip to Mars will last at least two years) and expose astronauts to a more damaging types of radiation, other strategies such as better shielding and mitigation strategies are necessary before astronauts can spend extended periods in deep space.

What Are Engineering Countermeasures?

Engineering countermeasures are structures or tools that are designed to shield astronauts from radiation. Depending on where astronauts are living and working, the radiation shielding requirements will vary because of exposure to different types and levels of radiation. The most penetrating ionizing radiation (gamma rays and galactic cosmic rays) can pass through aluminum but is stopped by thick and dense material such as cement. In general, the best shields will be able to block a spectrum of radiation. Aboard the space station, the use of hydrogen-rich shielding such as polyethylene in the most frequently occupied locations, such as the sleeping quarters and the galley, has reduced the crew's exposure to space radiation. Since the Space Shuttle and the International Space Station are in low Earth orbit, where the quantity and energy of the radiation is lower and the Earth's atmosphere provides protection, these spacecraft require less shielding than a base on the surface of the Moon. On the Moon, radiation shields would need to be very thick to prevent the primary cosmic rays (high-energy protons and heavy ions) from penetrating into habitation modules where astronauts will live. Such shielding could include the metal shell of a spacecraft or habitation module, an insulating layer of lunar water, or both.



The composition and thickness of a material affects its ability to shield radiation.

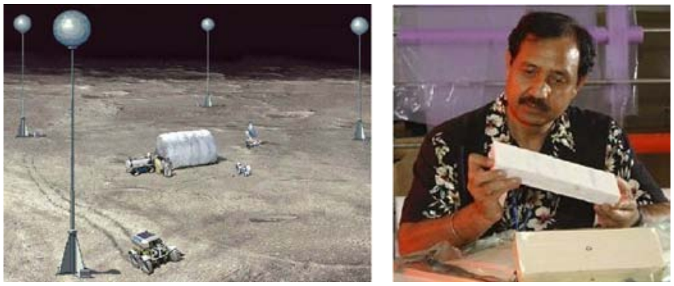


Collisions between high-energy radiation and shielding can produce damaging secondary particles.

Problems with shields arise when space radiation particles interact with the atoms of the shield itself. These interactions lead to production of nuclear byproducts called secondaries (neutrons and other particles). If the shield isn't thick enough to contain them, the secondaries that enter the spacecraft can be worse for astronauts' health than the primary space radiation. Surprisingly, heavier elements such as lead produce more secondary radiation than lighter elements such as carbon and hydrogen. Consequently, a great deal of research has been performed on a lightweight polyethylene plastic, called RFX1, which is composed entirely of lightweight carbon and hydrogen atoms.[41] Research shows that polyethylene is 50% better at shielding solar flares and is 15% better at shielding galactic cosmic radiation as compared to aluminum. Water is another hydrogen-rich molecule that can absorb radiation. However, the oxygen content in water makes it a lot heavier than polyethylene, and therefore is much more expensive to launch. Generally, lighter shields can greatly reduce the harmful effects of incoming space radiation particles, but they cannot completely stop them.

NASA scientists have also investigated the development of electrostatic radiation shields,[42] which generate positive and negative electric charges that deflect incoming electrically charged space radiation. Another method of radiation protection that has been proposed is to use the lunar regolith (the pulverized dusty material on the Moon's surface) to shield a human colony.

41 http://science.nasa.gov/headlines/y2005/25aug_plasticspaceships.htm
42 http://www.nasa.gov/centers/goddard/news/topstory/2004/0930grb.html

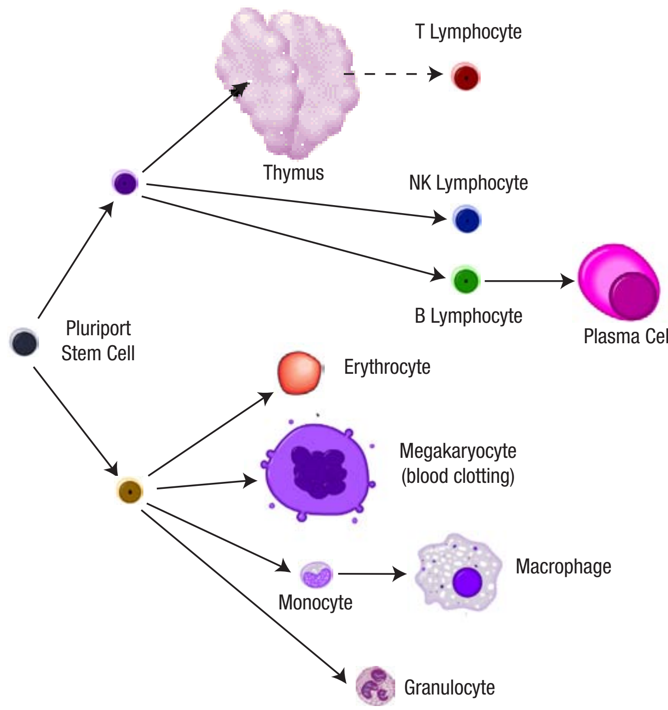


NASA has investigated electrostatic and plastic shielding. Combinations of different engineering, operational, and dietary countermeasuers help improve radiation protection. Image Credit: NASA Goddard Space Flight Center.

Although existing shielding can solve some radiation concerns, it makes spacecraft heavy and expensive to launch. Moreover, it does not provide complete protection against radiation. Shields five to seven centimeters thick can only block 30 to 35 percent of the radiation, which means that astronauts could still be exposed to up to 70 percent of the radiation that passes through the shields.[43] For this reason, NASA is also investigating the use of medical and dietary supplements to mitigate the effects of ionizing radiation.

What are Dietary Countermeasures?

Dietary countermeasures are drugs, that when ingested by an astronaut, may have the potential to reduce effects of ionizing radiation. These supplements can be broadly categorized into two groups. The first group includes specific nutrients that prevent the radiation damage. For example, antioxidants like vitamins C and A may help by soaking up radiation-produced free-radicals before they can do any harm. Research has also suggested that pectin fiber from fruits and vegetables, and omega-3-rich fish oils may be beneficial countermeasures to damage from long-term radiation exposure. Other studies have shown that diets rich in strawberries, blueberries, kale and spinach prevent neurological damage due to radiation. In addition, drugs such as Radiogardase (also known as Prussian blue) that contain Ferric (III) hexacyanoferrate (II) are designed to increase the rate at which radioactive substances like cesium-137 or thallium are eliminated from the body.[44]

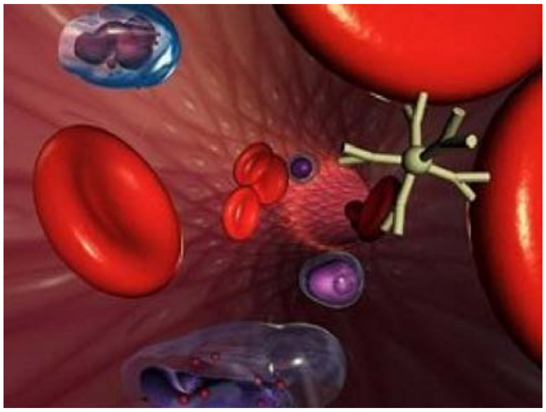


Stem cells in the bone marrow produce a wide range of blood cell types. Image Credit: Stem Cell World.

The second group of dietary agents currently being considered for protection against ionizing radiation includes drugs that can facilitate faster recovery from radiation damage. These dietary agents offer protection by stimulating the growth of surviving stem and progenitor cells, or by lengthening the duration of the cell cycle segment that checks for and repairs damaged genes.[45] Although these types of drugs (radioprotectants) are now used to treat people exposed to radiation contamination on Earth, they may be good candidates for use on long duration space missions. It is important to note, however, that when administered in effective concentrations, some radioprotectants also have limiting negative side effects such as nausea, hypotension, weakness, and fatigue.

One natural defense system is for an abnormal radiation damaged cell to self-destruct before the cell becomes cancerous; this is achieved by activation of the cell's apoptosis gene (programmed cell death). Apoptosis can also be triggered intentionally by exposing the cell to enzymes or specific ligands that bind to a cell's death receptors. Other approaches that may also be useful aim to enhance the DNA repair system and immunoresponse by facilitating faster recovery of cell populations damaged by radiation. There are several such pharmaceuticals now in clinical trials. Some drugs, for example, stimulate the immune system to "restore and repopulate" bone marrow cells after radiation exposure. Other drugs appear to reduce gene mutations resulting from radiation exposure.

43 http://www.nasa.gov/vision/space/travelinginspace/keeping_astronauts_healthy_prt.htm
44 http://www.fda.gov/bbs/topics/NEWS/2003/NEW00950.html
45 http://www.nasa.gov/vision/space/travelinginspace/keeping_astronauts_healthy_prt.htm


Dietary countermeasures have effects at the molecular level.
Image Credit: NASA.

Radiation protectants originally developed to protect military personnel in the event of nuclear warfare are now being used to protect cancer patients against the harmful effects of radiation treatment. Although large doses of ionizing radiation are damaging, small amounts are required for some biological processes. For example, vitamin D, necessary for maintenance and growth of bones, is normally produced in a person's skin through exposure to ultraviolet light. Since the Space Station is shielded to keep out harmful amounts of ultraviolet radiation, normal vitamin D production in an astronaut's skin is inhibited. To compensate, the astronauts will require vitamin D supplements.[46]

46 http://www.nasa.gov/vision/space/travelinginspace/keeping_astronauts_healthy_prt.htm