



MATH AND SCIENCE @ WORK

AP* **BIOLOGY** Educator Edition



RENAL STONE RISK TO ASTRONAUTS

Instructional Objectives

Students will

- review the structure and function of the urinary system, and apply the principles of diffusion, osmosis, and homeostasis to electrolyte and plasma fluid levels within the human body;
- examine the physiological impact of increased blood calcium levels and reduced urine output on the formation of renal (kidney) stones in microgravity environments;
- evaluate hydration, diet, and mineral supplements as countermeasures to renal stone formation; and
- understand the biochemical importance of calcium in human physiology with respect to muscle contractions and voltage-charged action potentials.

Degree of Difficulty

For the average AP Biology student, the problem is at an advanced difficulty level due to the complex biochemical and physiological processes involved in maintaining homeostasis within the human body.

Class Time Required

This problem requires 100–120 minutes.

- Introduction: 10–20 minutes
 - Read and discuss the background section with the class before students work on the problem.
- Student Work Time: 80 minutes
- Post Discussion: 10–20 minutes

Background

This problem is part of a series of problems that apply Math and Science @ Work in NASA's research facilities.

Dietary factors can contribute to increased loss of bone mineral density and increased risk of developing renal stones, especially for astronauts during spaceflight.

To address these physiological risks in spaceflight, NASA's Nutritional Biochemistry Laboratory carefully monitors both the dietary intake and body

Grade Level

10–12

Key Topic

Diffusion, Osmosis, Homeostasis, Human Physiology

Degree of Difficulty

Advanced

Teacher Prep Time

10–30 minutes

Class Time Required

100–120 minutes

AP Biology

Framework Alignment

Essential Knowledge:

2.B.1, 2.B.2, 2.B.3, 2.C.1, 2.C.2, 2.D.2, 2.D.3, 2.D.4

NSES

Science Standards

- Unifying Concepts and Processes
- Life Science
- Science in Personal and Social Perspectives
- History and Nature of Science

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mass of astronauts during their four to six-month-long missions on the International Space Station (ISS). Additionally, this laboratory studies the metabolic properties of specific nutrients in spaceflight.



Figure 1: A scientist processing urine samples in the Nutritional Biochemistry Laboratory at NASA Johnson Space Center

From spaceflight and ground-based studies, researchers are able to develop, evaluate, and validate nutritional countermeasures (or preventions) to minimize these negative effects of long-duration spaceflight on the human body. For example, researchers are currently exploring the amino acids in animal proteins and their effects on calcium metabolism.

Excessive amounts of sulfur-containing amino acids (cysteine and methionine) can metabolize to create a slightly acidic environment in the body. Basic components of the diet, such as potassium salts—found in fruits and vegetables—can help neutralize these acid loads. Because bone itself is a large reservoir of calcium-containing base, an increase in acidity can affect calcium metabolism when there is not enough base in the diet. The result can be an increase in bone demineralization.

Bone demineralization increases the risk of developing renal stones. Renal stones, popularly known as kidney stones, are small rock-like objects made from deposits of calcium and other minerals that form in the kidneys or urinary tract. Normally, calcium and protein, along with other minerals that build bone and muscle, are transferred to the bloodstream and then to the kidneys, where they are flushed out with bodily fluid. Without sufficient amounts of fluid, crystals can form and grow into stones. When stones block kidney drainage, they result in urinary obstruction and pain.

Renal stones can be extremely debilitating and, when they occur during spaceflight, can potentially end a mission. Medical therapy options that are widely available on Earth are severely limited during long-duration space exploration. Therefore, preventing renal stone formation is the most logical and cost-effective approach for spaceflight missions.

The benefits of using nutrition and altering dietary patterns as countermeasures include lowered risks for side effects, lowered costs, and minimal crew time required during spaceflight. Research studies in other discipline areas (i.e., cardiovascular, muscle, bone, immunology, and radiation) have indicated nutrition as integral in determining successful countermeasures, and confirm that additional efforts in nutrition research are still needed.

However, countermeasures for maintaining astronaut health in space are not limited to nutrition and dietary plans alone. Exercise and medication are two other countermeasures that are often used to address various spaceflight-related health concerns. It is this multi-disciplinary approach that will be necessary to ultimately enable safer human exploration of space.

Additional Research

It is suggested that students investigate scientific findings and current research on renal stone risk during spaceflight prior to completing this activity. Suggested articles can be found in the related resources section of this activity webpage:

http://www.nasa.gov/audience/foreducators/mathandscience/research/Prob_RenalStone_detail.html

AP Biology Framework Alignment

Big Idea 2: Biological systems utilize free energy and molecular building blocks to grow, to reproduce, and to maintain dynamic homeostasis.

- **Enduring understanding 2.B:** Growth, reproduction, and dynamic homeostasis require that cells create and maintain internal environments that are different from their external environments.
 - 2.B.1:** Cell membranes are selectively permeable due to their structure.
 - 2.B.2:** Growth and dynamic homeostasis are maintained by the constant movement of molecules across membranes.
 - 2.B.3:** Eukaryotic cells maintain internal membranes that partition the cell into specialized regions.
- **Enduring understanding 2.C:** Organisms use feedback mechanisms to regulate growth and reproduction, and to maintain dynamic homeostasis.
 - 2.C.1:** Organisms use feedback mechanisms to maintain their internal environments and respond to external environmental changes.
 - 2.C.2:** Organisms respond to changes in their external environments.
- **Enduring understanding 2.D:** Growth and dynamic homeostasis of a biological system are influenced by changes in the system's environment.
 - 2.D.2:** Homeostatic mechanisms reflect both common ancestry and divergence due to adaptation in different environments.
 - 2.D.3:** Biological systems are affected by disruptions to their dynamic homeostasis.
 - 2.D.4:** Plants and animals have a variety of chemical defenses against infections that affect dynamic homeostasis.

NSES Science Standards

Unifying Concepts and Processes

- Change, constancy, and measurement
- Form and function

Life Science

- The cell
- Matter, energy, and organization in living systems

Science in Personal and Social Perspectives

- Personal and community health
- Natural and human induced hazards

History and Nature of Science

- Science as a human endeavor
- Nature of scientific knowledge



Problem and Solution Key (One Approach)

In this problem, you will examine one of the adaptive effects of space travel on human physiology—a change in the chemical composition of urine that occurs both during spaceflight and after return to Earth. These biochemical changes in urine are known risk factors for the formation of renal stones.

Bone demineralization in microgravity environments results in increased blood levels of calcium and other minerals and proteins normally used for bone and muscle. These solutes travel through the bloodstream and are filtered by the kidneys, which results in increased calcium excretion in the urine. Without enough fluid to wash them away, crystals can form and develop into renal stones.

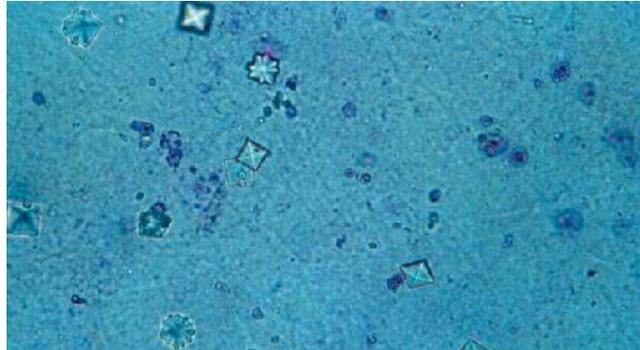


Figure 2: Micrograph showing calcium oxalate crystals in urine

- A. The function of the kidney, as it relates to overall health, is extremely important since it plays a crucial role in keeping the blood clean and regulating the amount of fluid in the body. Waste products and excess fluid are removed from the body through the production of urine which involves highly complex steps of excretion and reabsorption. This process is necessary to maintain a stable balance of body chemicals.
- I. Identify the primary filtration structure of the kidneys. Describe the process of blood filtration and how metabolic wastes and other toxic substances are removed from the body by the urinary system.

The primary filtration structure is the nephron, which regulates the amount of salts, water, sugar, and urea circulating in the body. Blood enters the kidneys through the renal arteries. Blood flows through the nephrons and filtration occurs in the glomerulus. Particles too large to diffuse, such as proteins and cells, remain in the bloodstream. Smaller particles, such as ions, sugars, urea, and other waste materials, pass through the membranes into Bowman's capsule. Any excess particles that need to be removed from the blood will diffuse out of the tubules and later be excreted.

- II. Explain how the kidneys' processes of filtration and reabsorption maintain the proper balance of water and electrolytes in the extracellular fluid.

In the glomerulus, filtration allows large molecules like hemoglobin and proteins to remain in the blood while the fluid (comprised of water, glucose, electrolytes, and urea) continues on through the kidney. Within the renal tubules, 99% of the additional water, electrolytes, urea, minerals, and amino acids needed for homeostasis are reabsorbed back into the bloodstream through passive absorption [moving with a concentration gradient] or active absorption [using transport carriers] according to the body's needs. The final stage of water and electrolyte reabsorption to ensure proper balance occurs in the collecting ducts, and is regulated by the hormones ADH and aldosterone.



B. In microgravity, decreased urine volumes are accompanied by increased urinary excretion of calcium. This greatly increases the chances of developing renal stones.

I. Discuss the role of calcium in the formation of renal stones.

Approximately one-half of the calcium ions in the human body bind to anions forming calcium salts. Since calcium salts exhibit low solubility in aqueous solutions (meaning they don't readily dissolve), an excess of undissolved calcium salt compounds may form crystals that slowly build up into renal stones, especially when there is inadequate water flowing through the kidneys.

II. Evaluate the health risks involved with developing renal stones during spaceflight.

The formation of renal stones may present a range of symptoms from mild discomfort to excruciating pain in the lower abdomen. This could render an astronaut incapable of performing the required duties on a mission. In some cases, infection may occur, which can be serious and would need immediate medical attention. Surgery could be required if the stone is too large to pass on its own, if there are indications that it is growing, or if it is blocking the urine flow, causing a urinary tract infection or kidney damage. Because of the limited medical supplies available in space, the mission could be ended for the astronaut to return to Earth.

III. Renal stones can usually be prevented by modifying fluid intake, adjusting the diet, and taking medication. Choose two of the three preventative measures listed below and explain how each could be used to lower the risk of renal stone formation in astronauts during spaceflight.

- Increasing the amount of water consumed during spaceflight
- Reducing the amount of salt in the astronaut's diet
- Taking potassium citrate supplements

Students should choose two of the options and give correct explanations for their choices. Explanations of each are as follows:

- *Drinking large volumes of water each day will dilute the mineral or stone-forming salts in the urine.*
- *Salt is made up of sodium and chloride. The sodium in salt, when excreted by the kidneys, causes more calcium to be excreted into the urine. High concentrations of calcium in the urine combine with oxalate and phosphorus to form stones. Reducing salt intake is preferred to reducing calcium intake.*
- *Potassium citrate is a common preventive treatment for renal stones because when the citrate binds to calcium in the urine, it creates a highly soluble complex and prevents the calcium from crystallizing and developing into a stone. Citrate also makes the urine less acidic, reducing the risk of uric acid stones.*

C. Sulfur-containing amino acids in animal protein, as well as chlorides and phosphates in the diet, act as acid precursors. They are commonly associated with increased urinary calcium excretion and lower urine pH. Anions, including conjugate bases of organic acids, are base precursors. A diet high in sulfur-containing amino acids may increase acid load in the body and lead to the resorption (or loss) of bone mineral (calcium carbonate) and increased calcium excretion. This



may result in an increased risk of renal stone formation due to an imbalance in the body's acid-base homeostasis.

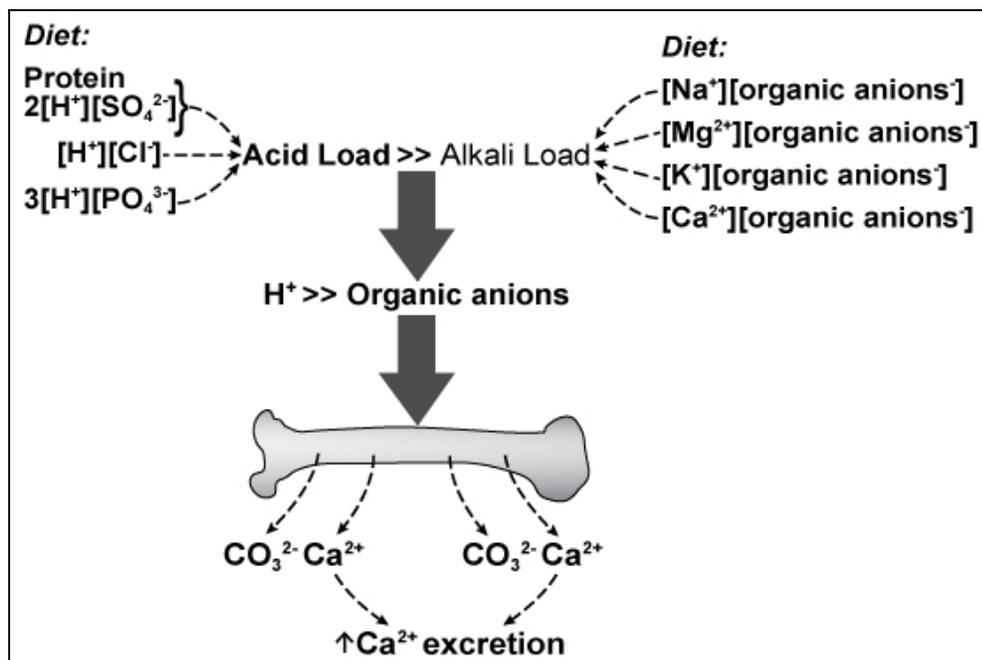


Figure 3: Schematic of acid-base homeostasis and the effects on bone of an increased acid load. *Int. SportMed J.* 6(4): 199–214 (2006)

- I. If you were a dietician, what nutritional recommendations would you make to decrease the acid load and achieve acid-base homeostasis?

Example recommendations:

- Increase fruit and vegetable consumption to counteract a high net acid load
 - Decrease the consumption of proteins with sulfur-containing amino acids to counteract a high net acid load
 - Rather than animal protein, substitute a different source of protein that doesn't contain sulfur-containing amino acids to counteract a high net acid load
- II. The presence of calcium in the body is critical to more than just bone formation. Explain the role that calcium plays in either skeletal or cardiac muscle contractions.

Calcium ion channels are present in skeletal muscle fibers and, when activated, allow calcium ions to flood in and around the myofibrils, bathe the sarcomeres, interact with regulatory proteins associated with actin, and induce sarcomere contractions that allow the muscle to shorten (or contract). Skeletal muscles also contain an organelle, the sarcoplasmic reticulum, which stores large quantities of calcium. When a skeletal muscle cell is stimulated, most of the calcium that bathes the sarcomeres actually comes from the sarcoplasmic reticulum.

Cardiac muscle contraction requires an inward flux of extracellular calcium ions through L-type calcium channels which prolong the depolarization of cardiac muscle cells. Once the intracellular concentration of calcium increases, calcium ions bind to the protein



topoinin. This initiates contraction by allowing the contractile proteins, myosin and actin, to associate through cross-bridge formation.

Scoring Guide

Suggested 10 points total to be given.

There are up to 3 additional points possible to earn; however, students should not receive more than 10 total points for the questions or more than the allotted points per question.

| Question | Distribution of points |
|-------------------|---|
| A 3 points | 1 point for correct identification of kidney filtration structures (nephrons) 1 point for correctly describing the filtration process steps 1 point for correctly explaining how homeostasis is maintained through the processes of filtration and reabsorption *1 additional point for elaboration on hormones ADH and aldosterone |
| B 4 points | 1 point for discussion of how the insolubility of calcium salts and/or decrease in water content in urine contribute to undissolved calcium compounds forming stones 1 point for mentioning at least two of the following scenarios: pain, infection, surgery, kidney damage, etc. 1 point <i>each</i> for correctly explaining how two of the countermeasures listed will aid in the prevention of renal stones in microgravity *1 additional point for elaboration on calcium citrate being highly soluble and lowering urine pH |
| C 3 points | 1 point for correctly recommending one of the following: increasing vegetables and fruits, decreasing sulfur-containing protein sources, or substituting other protein sources 2 points for correctly explaining the skeletal muscle contraction or cardiac muscle contraction with relation to calcium channels and Ca ⁺⁺ induced action potentials *1 additional point for elaboration on interaction of calcium with regulatory proteins associated with actin and myosin |

Contributors

This problem was developed by the Human Research Program Education and Outreach (HRPEO) team with the help of NASA subject matter experts and high school AP Biology instructors.

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