Space physiology within an exercise physiology curriculum

Jason R. Carter1 and John B. West2
1Department of Kinesiology and Integrative Physiology, Michigan Technological University, Houghton, Michigan; and 2Department of Medicine, University of California-San Diego, La Jolla, California

Submitted 12 April 2013; accepted in final form 17 July 2013

Carter JR, West JB. Space physiology within an exercise physiology curriculum. Adv Physiol Educ 37: 220–226, 2013; doi:10.1152/advan.00035.2013.—Compare and contrast strategies remain common pedagogical practices within physiological education. With the support of an American Physiological Society Teaching Career Enhancement Award, we have developed a junior- or senior-level undergraduate curriculum for exercise physiology that compares and contrasts the physiological adaptations of chronic terrestrial exercise (TEx) and microgravity (μG). We used a series of peer-reviewed publications to demonstrate that many of the physiological adaptations to TEx and μG are opposite. For example, TEx typically improves cardiovascular function and orthostatic tolerance, whereas μG can lead to declines in both. TEx leads to muscle hypertrophy, and μG elicits muscle atrophy. TEx increases bone mineral density and red blood cell mass, whereas μG decreases bone mineral density and red blood cell mass. Importantly, exercise during spaceflight remains a crucial countermeasure to limit some of these adverse physiological adaptations to μG. This curriculum develops critical thinking skills by dissecting peer-reviewed articles and discussing the strengths and weaknesses associated with simulated and actual μG studies. Moreover, the curriculum includes studies on both animals and humans, providing a strong translational component to the curriculum. In summary, we have developed a novel space physiology curriculum delivered during the final weeks of an exercise physiology course in which students gain critical new knowledge that reinforces key concepts presented throughout the semester.

microgravity; integrative physiology; kinesiology; pedagogy

EXERCISE PHYSIOLOGY is a common undergraduate course at most 4-yr comprehensive universities in the United States and worldwide. It is typically a required course for Kinesiology degrees, particularly ones with an emphasis on prehealth education. Moreover, exercise physiology is often a recommended course for students pursuing prehealth education through other departments and degrees (i.e., Physiology, Biological Sciences, Neurobiology, Biomedical Engineering, etc.). Some sort of basic anatomy and/or physiology course is usually a prerequisite, allowing instructors to explore in greater depth the acute and chronic adaptations associated with exercise. Typical topics covered include bioenergetics and exercise metabolism, muscular adaptations to exercise, cardiovascular adaptations to exercise, respiratory control during exercise, neuroendocrine control during exercise, the physiology of training, influence of altitude on exercise, thermal control during exercise, and many other topics. Most instructors who teach a 14- to 15-wk semester of exercise physiology find it challenging to get through a typical textbook and often find themselves having to pick and choose areas to emphasize.

The focus of the exercise physiology curriculum at Michigan Technological University has been on bioenergetics/exercise metabolism and the effects of exercise on basic physiological systems (i.e., cardiovascular, musculoskeletal, renal, respiratory, neural, endocrine, etc.). Given the emphasis on the effects of acute and chronic exercise on basic physiological systems, our exercise physiology curriculum is heavily focused on integrative concepts. These physiological systems rarely work in isolation, and, in many ways, the human body is masterfully designed to have redundancies. When neural responses to exercise are discussed, endocrine responses are integrated. When cardiovascular adaptations to exercise are discussed, it is difficult to do so without the integration of concepts from the respiratory and renal systems. Accordingly, J. R. Carter developed a unique end-of-the-semester curriculum that emphasizes this integration and reinforces key concepts delivered throughout the semester. Specifically, a “space physiology” curriculum is incorporated during the final 2 wk of class that has generated positive student feedback over the past 4 yr. Briefly, students are shifted away from the normal exercise physiology textbook toward some peer-reviewed literature. The literature includes both review and original articles and is focused on physiological adaptations associated with microgravity or simulated microgravity. The students apply the core knowledge they’ve obtained throughout the year and soon realize that most physiological adaptations to microgravity are opposite to terrestrial exercise.

The American Physiological Society funds a Teaching Career Enhancement Award program aimed at allowing individuals to “develop innovative and potentially widely applicable programs for teaching and learning physiology.” This award mechanism allowed J. R. Carter to visit the University of California-San Diego to work with J. B. West on the development of this curriculum for broader dissemination to the scientific and teaching community. J. B. West has continuously been funded by the National Aeronautics and Space Administration (NASA) for >30 yr and has published numerous scientific and historical articles about physiological adaptations to microgravity. The visit also allowed interactions with other University of California-San Diego faculty members/scientists familiar with physiological education and/or the physiology of microgravity. Detailed below is a four-class curriculum that aims to generate excitement with students at a time when they are ready for the semester to end. More importantly, this novel space physiology curriculum helps to reinforce key exercise physiology concepts presented throughout the semester.

Finally, while this report is geared toward exercise physiology courses, it is important to recognize that the compare/contrast strategies between space and exercise physiology can be applied to more general undergraduate physiology courses or even advanced graduate-level courses exploring physiological adaptations to exercise and stress. While we will focus
primarily on curricular implementation for an exercise physiology course, we are hopeful this report, and the highlighted peer-review articles and activities, can be more broadly applied to more general physiology courses that include sections on physiological adaptations to exercise.

Curriculum for Exercise Physiology

Day 1: overview and historical context. Students are asked to come to the first class having read West et al. (9), the opening article for a series of invited reviews highlighting the physiological adaptations associated with microgravity (Perspective on historical perspectives. J Appl Physiol 89: 326, 2000). It is important to note that much of the presented data in this series came from the highly successful SpaceLab Life Sciences missions and that they remain remarkably relevant and up to date because of the limited number of physiological studies performed in microgravity over the past 13 yr. While there are more recent reviews on some of the topics, we still find aspects of this series invaluable given the comprehensive nature of the reviews.

The recommended article is an excellent primer for this curriculum for a couple reasons. First, it provides a nice transition from the typical textbook readings that the students have encountered all semester to the more intense scientific, peer-reviewed readings they will be exposed to over the 2-wk microgravity curriculum. Second, the first half of the recommended article (9) includes a detailed historical comparison of the United States and Soviet Union/Russian space race, with an obvious focus on physiological responses and adaptations. Our experience is that students find this historical discussion invigorating at a time when they are looking forward to the end of the semester. In fact, student evaluations of the class consistently include positive comments that suggest the novelty of the subjects hits at the right time and makes for a unique and dynamic learning experience.

In addition to the historical context, the recommended article (9) includes a succinct introduction into some of the physiological responses to microgravity that are covered in subsequent classes. These short descriptions of orthostatic intolerance (OI), bone demineralization, muscle atrophy, and loss of red blood cell mass associated with microgravity are more scientific than the historical section and set the stage for an inquiry-based discussion with the students. More specifically, these short descriptions allow for the course instructor to ask how these microgravity adaptations compare with what has been learned throughout the semester regarding the chronic adaptations of terrestrial exercise. Most students will immediately recognize that the vast majority of microgravity adaptations are opposite to the adaptations associated with chronic terrestrial exercise (Table 1). However, there is always a handful of students who recognize that some responses/adaptations are actually similar under certain conditions (i.e., OI in some highly trained athletes and improved blood-gas perfusion ratios; discussed further below).

We encourage questions and discussion this first day. When combined with a couple short NASA or YouTube videos on spaceflight, this initial article (9) seems appropriate to fill a 50- to 55-min class. Incidentally, at the time of this article, there is an excellent YouTube video on the International Space Station at http://youtube.com/embed/doN4t5NKW-k. When we have attempted to include an original article, as done with several of the subsequent days, there is usually little time and the class seems less likely to fully engage in discussion.

Day 2: bone adaptations to microgravity. It is widely recognized that bone adaptations may be one of the major critical factors associated with long-duration spaceflight (i.e., a mission to Mars). While most of the detrimental physiological adaptations to microgravity can be reversed upon return to Earth (even after very-long-duration spaceflight), there is evidence to suggest that some of the bone loss associated with microgravity may never recover. Turner (7) wrote an excellent review that demonstrates the effects of short- and long-term microgravity on bone in both animal and human models.

The Turner article (7) begins with a brief description of weight versus gravity. This is a wonderful opportunity to ask the students to “remember” some of the basics they learned in college physics 101, assuming the students have had physics in their curriculum. Specifically, we suggest using the classic Newtonian experiment of a cannon shot from a fictitiously tall mountain going into freefall (Fig. 1). This is a solid visual that allows students to identify with the concept that orbital spaceflight is really a perpetual state of freefall that results in weightlessness. In reality, orbital spaceflight results in very minimal changes in “gravity” (i.e., an astronaut’s distance from the center of the Earth actually only increases by <5%). This is why it is technically inappropriate to say that orbital spaceflight is “zero gravity” (0G), as stated occasionally. This is also a great opportunity to explain to the students why parabolic flight can provide brief periods of simulated microgravity (i.e., the freefall concept).

After the establishment of microgravity associated with orbital spaceflight, we transition to the basics of what is known about spaceflight on human bone and mineral metabolism. We begin by asking students to identify some of the limitations associated with human studies in space. Answers include the following: limited sample size and variations in age, nutritional intake, exercise levels, flight duration, etc. Despite these limitations, spaceflight studies on human bone have consistently demonstrated chronic changes in calcium balance. More specifically, spaceflight is associated with a negative calcium balance that is believed to be due to 1) reduced absorption and 2) increased excretion. It is also important to highlight that bone adaptations are site dependent, with the greatest bone losses in pelvic bone, lumbar vertebrae, and femoral neck (i.e., weight-bearing bones). Figure 2 highlights some of the bone adaptations associated with microgravity.

<table>
<thead>
<tr>
<th>Factors Subject to Physiological Adaptation</th>
<th>Exercise Adaptation</th>
<th>Space Adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone mineral density</td>
<td>Increases</td>
<td>Decreases</td>
</tr>
<tr>
<td>Net calcium balance in bone</td>
<td>Improves</td>
<td>Worsens</td>
</tr>
<tr>
<td>Muscular adaptation</td>
<td>Hypertrophy</td>
<td>Atrophy</td>
</tr>
<tr>
<td>Muscular fatigue</td>
<td>Decreases</td>
<td>Increases</td>
</tr>
<tr>
<td>Cardiovascular function</td>
<td>Improves</td>
<td>Worsens</td>
</tr>
<tr>
<td>Red blood cell mass</td>
<td>Increases</td>
<td>Decrease</td>
</tr>
<tr>
<td>Terrestrial orthostatic tolerance</td>
<td>Improves*</td>
<td>Worsens</td>
</tr>
</tbody>
</table>

*Some highly trained endurance athletes actually demonstrate declines in terrestrial orthostatic tolerance, and this difference is relevant to the proposed curriculum.
Animal studies on bone adaptations during spaceflight are much more extensive. Additionally, the animal model affords some advantages, such as controlled conditions (i.e., nutrition, exercise, etc.), a homogeneous population, and more invasive techniques. However, one major limitation acknowledged is that due to weight restrictions and the desire to maximize statistical power, most studies use young, growing rats. This is another great opportunity to ask students why this is not ideal, and students recognize that astronauts are adults who are no longer growing. In fact, many astronauts are at an age where quite the opposite may be occurring (i.e., osteoporosis). Nevertheless, animal studies have provided important insights that human studies have not. Specifically, we suggest highlighting three major findings: 1) bone formation may be inhibited as early as 4 days into spaceflight, and this may be associated with reductions in mRNA levels for bone matrix proteins; 2) spaceflight appears to inhibit bone formation and induce bone loss at cancellous sites (may need to review bone structure with the students); and 3) these bone adaptations may inhibit normal bone repair of a fracture during spaceflight. Again, we emphasize that these adaptations are most prominent in weight-bearing bones and discuss why this makes sense from a physiological perspective.

After this overview discussion of the Turner article (7), we transition to an original article examining spaceflight and bone. Given the objective to contrast with the semester-long emphasis on exercise physiology, we discuss an article examining the influence of exercise training on bone adaptations during spaceflight. One could choose either in animal- or human-based studies, but we suggest using Shackelford et al. (6), a simulated microgravity study in humans. We begin all of our original articles with a brief discussion of the rationale and hypothesis. In the case of Shackelford et al. (6), the authors nicely outlined the various spaceflight countermeasures for combating bone loss and made a convincing case for resistance training, which is commonly used by current astronauts on the International Space Station. Their hypothesis was that bone loss, primarily assessed via bone mineral density (BMD) and calcium balance, would be significantly reduced in an exercise group compared with a control group. Both groups were exposed to 17 wk of bed rest. In discussing the METHODS, it is a great opportunity to ask questions about how things might have been done differently; a typical answer is to have incorporated a head-down tilt bed rest model, but students also acknowledge such a change could negatively influence dropout rates and subject compliance (discussed in the article). The RESULTS section demonstrates that resistance training had a positive treatment effect with nearly all bone markers, and we emphasize the changes in observed lumbar spine BMD (+3% vs. −1%), calcaneus BMD (+1% vs. −9%), parathyroid hormone concentration (+18% vs. −25%), and net calcium balance (+21 vs. −199 mg/day).

In summary, it is presently impossible to predict the bone health risk of long-term spaceflight. More controlled research studies are needed in both human and animal models. It is critical to acknowledge that while many of the other physiological adaptations associated with microgravity (i.e., cardiovascular, skeletal, etc.) can be reversed after return to Earth, there is evidence to suggest that some bone adaptations may never be completely reversed (7). Along with space radiation, bone adaptation is a major rate-limiting problem associated with a long-term human space mission to Mars and beyond. However, exercise countermeasures, particularly resistance exercise, may play a key role in addressing the deleterious bone adaptations associated with microgravity.

Day 3: muscular adaptations to microgravity. Any good exercise physiology curriculum is going to contain an in-depth discussion of muscular adaptations to both acute and chronic exercise. This will include discussions on the skeletal muscle structure, sliding filament theory, excitation-contraction coupling, fiber type and adaptation, force- and power-velocity concepts, etc. Given the amount of information and the importance of the skeletal muscular system within an exercise phys-
ioletry curriculum, you will have to pick and choose what to emphasize and focus on. We recommend consideration of one of two review articles (3, 5). Additionally, given the depth associated with both of these review articles, we do not recommend an additional original article for this section; there is simply not enough time (unless there is a willingness to devote a second class to the topic). We will focus most of our discussion below on Fitts et al. (3), and we recommend focusing on six basic aspects of that article.

First, beware that while Fitts et al. (3) is a phenomenal and indepth review of the skeletal muscle adaptations associated with microgravity, it is a high-level read for anyone not intimately familiar with skeletal muscle function (especially junior/senior-level undergraduate students). Thus, we recommend that this section begin with a brief review of the skeletal muscle fiber types and the human anatomy of the soleus, medial gastrocnemius, and tibialis anterior muscles (the three skeletal muscles most affected by microgravity); this will help students transition from their prior knowledge to this muscular-microgravity discussion. We emphasize that similar to bone adaptations, most microgravity-induced muscular adaptations occur in muscles involved in weight-bearing activities.

Second, we highlight the Fitts et al. (3) discussion related to differences between rat and human studies. Specifically, microgravity elicits greater atrophy in type I fibers compared with type II fibers in rats, and this atrophy occurs quite rapidly (i.e., 37% reduction in the soleus muscle after only 4–7 days of spaceflight). In contrast, studies have suggested that type II human fibers are more susceptible to atrophy than type I fibers (the opposite of rat studies). While the reasons underlying this difference have not been fully elucidated, the authors suggest it may be due to the average preflight fiber size (the type IIa fiber in rats is smaller compared with the type I fiber, whereas the human type IIa fiber seems to be slightly larger than the type I fiber). This is also a great opportunity to again discuss the strengths and weaknesses of human and animal studies and emphasize the importance of translational research.

Third, we recommend discussing the section on microgravity and cell proteins (3). Specifically, studies in rats have demonstrated that spaceflight increases hybrid fibers by inducing fast myosin expression in slow fibers with little to no influence on fast fibers. Consistent with terrestrial atrophy, spaceflight atrophy is associated with a drop in total protein, which appears to mirror the decline in muscle mass. The loss of muscle protein in humans is most likely due to a decline in synthesis, as studies have suggested minimal muscle breakdown detected in excretion and decreased energy intake during microgravity. Interestingly, rats exposed to microgravity appear to reduce protein synthesis at the transcription/translation level and downregulate the β-myosin heavy chain gene.

Fourth, spaceflight appears to reduce peak force of limb skeletal muscles in both rats and humans. The decline can range from 12% to 40%. One important question to ask students is why does spaceflight induce greater atrophy and force decline in the soleus compared with the gastrocnemius muscle? Fitts et al. (3) suggested that it may be due to reorganization of motor recruitment, favoring fast over slow fibers and/or flexors over extensors. This is an opportunity to review peak force relationships discussed earlier in the semester.

Fifth, there is a section in Fitts et al. (3) that pertains to muscle fatigue and damage. Regarding fatigue, it is suggested that spaceflight fatigue may be the result of accelerated glycogen utilization and reduced fat oxidation. This is an excellent opportunity to ask students how this might relate to a concept that was hopefully discussed earlier in the semester. Specifically, the accelerated glycogen utilization and reduced fat oxidation will lead to elevated concentrations of H⁺ and inorganic phosphate, both of which are known to directly inhibit cross-bridge formation. While this theory is largely conceptual, it affords an opportunity to revisit the role of ATP and H⁺ in cross-bridge formation. Regarding muscular damage, there is not sufficient evidence for damage during spaceflight, but there is clear evidence for muscular damage upon return (i.e., reloading and adaptation to the 1-G environment).

Finally, the Fitts et al. (3) article ends with a brief discussion regarding the importance of exercise as a countermeasure to the muscle atrophy associated with microgravity and suggests that future work is necessary to determine the role of exercise mode, frequency, and duration. As with bone, it is evident that resistance training is a critical countermeasure, but given the possible changes to both type I and Type II fibers during microgravity, there may be an optimal mixture of isometric versus isotonic exercise. Moreover, there is some evidence from rat studies to suggest that short periods of exercise interspersed throughout a day may be beneficial, but the feasibility of such practice with astronauts remains unclear.

An alternative to the Fitts et al. (3) article is a more recent review by Narici and de Boer (5). This article (5) can be a bit more appropriate for undergraduate students but does not contain the detail of the Fitts et al. (3) article. However, one advantage is that Narici and de Boer (5) included a more indepth discussion of exercise countermeasures and a very nice discussion of potential pharmacological and nutritional interventions. Thus, one possibility to keep things somewhat focused (and within 1 day) is to have students focus their primary reading on the Fitts et al. (3) article but also supplement that reading with the two-page section on countermeasures presented by Narici and de Boer (5). Figure 3 highlights some of the muscular adaptations associated with microgravity, with some comparison between animal and human studies.

Day 4: cardiovascular adaptations to microgravity. Since the first manned missions of Project Mercury, postspaceflight OI has been a consistent finding in astronauts returning from both short- and long-term microgravity. There are numerous review and original articles addressing postspaceflight OI, but we encourage the use of Convertino and Cooke (2) as a starting point. In this review (2), the authors focused on the cardiovascular risks outlined by NASA in the Bioastronautics Critical Path Roadmap. The authors make the case that there are certain areas identified by the Cardiovascular Alterations Discipline Team that are not strongly supported by the literature, whereas others indeed represent legitimate risks for astronauts.

The authors suggested that there are three cardiovascular risks supported by the literature. First, it has been suggested that long-duration spaceflight may lead to diminished cardiac function. Indeed, it is clear from numerous studies that stroke volume is reduced postspaceflight. This lower stroke volume has been associated with reduced cardiac size and left ventricular mass. Thus, spaceflight may lead to cardiac remodeling and compromised diastolic function. Convertino and Cooke (2) argued that these adaptations are appropriate adaptations to the microgravity environment and pose no major risk in flight.
However, these adaptations can contribute to postspaceflight OI and reduced work capacity, which are the true operational risks as they could compromise an emergency egress from a shuttle upon return to Earth. These microgravity adaptations, particularly the reduced left ventricular mass, can be contrasted to the adaptations to chronic exercise discussed earlier in the semester.

Second, Convertino and Cooke (2) support the concept of diminished vascular function with long-term spaceflight. They discussed the classic study of Buckey et al. (1), an article we strongly suggest as the original article for this section. Specifically, Buckey et al. (1) examined the hemodynamic responses to a stand test pre- versus postspaceflight. The novel aspect of the study was the categorization of astronauts into “finishers” and “nonfinishers,” as defined by their ability to finish a 10-min stand test (1). The primary finding was a significantly lower peripheral vascular resistance response to standing in the nonfinishers (i.e., less vasoconstriction). In addition to this excellent study by Buckey et al. (1), Convertino and Cooke (2) included other studies and data demonstrating reduced plasma volume and baroreflex dysfunction with microgravity. In summary, the authors provide evidence to suggest that although the mechanisms underlying postspaceflight OI are multifactorial, they likely include lower plasma volume, reduced stroke volume and cardiac output, reduced ability to constrict blood vessels in the lower extremity, and reduced baroreflex function.

Third, the article by Convertino and Cooke (2) highlights that several studies support the concept that long-term spaceflight significantly reduces aerobic capacity. Much like the prior discussion on postflight OI, this remains a major risk for operation performance, especially if extravehicular activity or an emergency egress during a landing is required. In summary, the review by Convertino and Cooke (2) provides a rationale for more countermeasure research aimed at restoring central blood volume, stroke volume, vasoconstrictive reserve, and baroreflex function. All of these concepts can logically be tied back to cardiovascular concepts presented during the exercise physiology core. However, this also presents a unique opportunity to highlight that not all microgravity adaptations are opposite to all exercise adaptations. Specifically, we suggest asking the students if there are any circumstances where cardiovascular conditioning can lead to any of the microgravity-induced symptoms. Hopefully a student will remember the discussion earlier in the semester about very highly trained athletes having problems with orthostatic tolerance (i.e., fainting). This is another great opportunity to reinforce a key concept learned earlier in the class without students even realizing it.

Although we spend the vast majority of this section discussing postspaceflight OI and reductions of aerobic capacity during spaceflight, we also discuss the contrasts regarding plasma volume and red blood cell mass. Specifically, while exercise is typically associated with increases in plasma volume and red blood cell mass, microgravity is associated with reductions in both plasma volume and red blood cell mass (Fig. 4). In fact, this reduction in red blood cell mass was noticed as early as the Gemini missions (9).

As mentioned above, one original article we recommend for this section is the classic work of Buckey et al. (1). However, there are numerous options, and we have also used articles by Watenpaugh et al. (8) and Iellamo et al. (4). Briefly, Watenpaugh et al. (8) tested the hypothesis that daily exposure to short periods of lower body negative pressure immediately after exercise would improve the OI associated with 30 days of 6° head-down bed rest. What is interesting about this article, and appealing to the students, is the use of identical twins within the experimental paradigm. The authors reported that the lower body negative pressure after exercise provided some

Fig. 3. An illustration of key muscular adaptations associated with microgravity. MHC, myosin heavy chain.

Fig. 4. An illustration of key cardiovascular adaptations associated with microgravity. BRS, baroreflex sensitivity; OI, orthostatic intolerance.
benefit but did not fully prevent the OI associated with 30 days of 6° head-down bed rest. In contrast, a study by Iellamo et al. (4) examined the influence of spaceflight on the muscle metaboreflex, thus allowing the potential connection to discussions on the metaboreflex from earlier in the semester. In this study, the authors reported an enhancement of the muscle metaboreflex during dynamic exercise in space and that this augmented metaboreflex may influence the cardiovagal baroreflex. This article is limited to only four astronauts and did not include postflight data because the data were collected from the Columbia mission that disintegrated during reentry in 2003; both generate discussion and careful reflection.

Finally, this section also presents an opportunity to remind students of the realities of scientific hypothesis testing. Specifically, we suggest asking the students to predict (i.e., hypothesize) the effects of microgravity on central venous pressure (CVP). This is yet another opportunity to discuss what happens during terrestrial exercise. Hopefully the majority of students will hypothesize that CVP will increase during spaceflight, presumably due to redistribution of blood flow. Interestingly, the opposite is true; microgravity is associated with a decrease in CVP. However, we suggest telling them to fear not, because they are in great company. The entire scientific team of PhD and MD scientists associated with the 1997 Neurolab mission unanimously predicted microgravity would increase CVP (personal communication with K. Prisk). It remains unclear why microgravity is associated with a paradoxical decrease in CVP, but it has been suggested that it may be due to some of the assumptions regarding the actual measurement technique in spaceflight (i.e., reference points). Additionally, some have suggested that it is the transmural pressure, not the intramural CVP, that is important; currently we do not know the influence of microgravity on the pressure outside the veins. This CVP example demonstrates to the students that 1) scientists are human and make mistakes and 2) key questions regarding microgravity and cardiovascular control remain.

Curriculum Implementation

There are likely a variety of ways to implement this curriculum into a class. The students we teach are mostly junior- or senior-level undergraduate students, with an occasional first-year graduate student. The class size is ∼30–40 students, and classes meet 3 days/wk (50 min/day) for ∼12 wk before the implementation of this space physiology curriculum. A two-semester general Anatomy and Physiology undergraduate course serves as the prerequisite for exercise physiology. Below are some implementation strategies we suggest for consideration (see Table 2 for a summary); such strategies may need modification as levels of education, class sizes, or other assumptions differ across institutions.

**Emphasis of curriculum throughout the semester.** We set the stage for this curriculum up the very first day of class when we hand out and discuss the syllabus. We highlight that the semester will wrap up with a series of peer-reviewed articles on space physiology that will challenge the students to compare/contrast with what they have learned for the preceding 12 wk. Also, at approximately the midpoint of the semester, we introduce them to a peer-reviewed article in the field of neural control of circulation during exercise (since this is a strength of the instructor’s research laboratory). This is another opportunity to foreshadow the upcoming peer-reviewed curriculum.

**Providing articles in a timely manner.** We upload the peer-reviewed articles to our e-learning system (i.e., Canvas) 2 wk before the start of this curriculum. This provides students an opportunity to read ahead of time, and it sends the message that reading these articles is not optional. We emphasize that it would be unwise to attend class without reading because 1) it will limit their ability to participate and 2) will negatively impact their grade because we have short quizzes each day before the class discussion begins.

**Daily quiz.** At the beginning of each class for this space physiology curriculum, we administer a short 8- to 10-question quiz. The quiz consists of four to five questions on the discussion from the previous day and four to five questions regarding the articles students were supposed to read. The questions are not designed to be incredibly difficult and tricky; we simply want to provide the students with extra incentive to stay engaged and attend the class discussions.

**Transition into day 1.** Up to this point, students have had little experience with peer-reviewed publications. We have already outlined previously some of the important things to
consider regarding day 1 (i.e., only one article, mixing history and science, inclusion of a YouTube video, etc.) to generate excitement.

Close the loop each day. Our ultimate goal with this curriculum is to reinforce concepts learned throughout the semester. This article has provided numerous examples of how we close the loop with students and challenge them to relate what they are learning that day (i.e., cardiovascular adaptations to space, muscular adaptations to space, etc.) to subsequent topics covered earlier in the semester. We end each day with a compare/contrast wrap-up discussion.

Small-group breakouts. One strategy we’ve taken in the past is to pose certain questions and provide students some time to discuss them in small groups (2–3 students/group) before answers are provided. For example, when we are discussing the pros and cons of animal versus human research, this is an opportunity we have used for this approach. Student groups are then asked verbally to share their group consensus in an open discussion.

Student examination and grading. As outlined previously, we have the students take a short 8- to 10-point quiz at the start of each day associated with this curriculum. These account for ~10% of their overall grade when other examinations and case studies are factored in. Moreover, our exercise physiology course includes a comprehensive final exam. The examination is primarily essay based, and one of the essay question always relates to comparing and contrasting space and exercise physiology.

Inclusion of a laboratory activity. Many exercise physiology courses have a laboratory associated with the course, including exercise physiology at our institution. We have not yet incorporated a specific laboratory related to this curriculum, but in preparing this article, it has become obvious that there are several excellent opportunities for this. For example, we envision the potential development of a laboratory module involving 6° head-down tilt and cardiovascular responses (or cardiovascular responses to lower body negative pressure since our institution has such equipment). The challenge is determining the potential development of a laboratory module involving 6° head-down tilt and cardiovascular responses (or cardiovascular responses to lower body negative pressure since our institution has such equipment). The challenge is determining where to fit such a module in and/or what it would replace in an already very full laboratory curriculum; nevertheless, we acknowledge this could potentially be a valuable implementation strategy.

Limitations

We have cautiously referenced some positive student feedback regarding this curriculum, but this feedback is based on 1) optional write-in comments associated with student evaluations and 2) direct feedback from students who have visited during office hours and/or optional review sessions; neither are conducive to quantitative assessment. We acknowledge the lack of direct assessment as a limitation and recognize this as a logical next step in the progression of this curriculum.

Summary

Since President Eisenhower established NASA in 1958, the organization has stimulated American ingenuity and scientific research. Over the last 55 yr, we’ve come to understand that microgravity has profound influences on the human body. Among other adaptations, spaceflight is associated with bone demineralization, muscle atrophy, and cardiovascular deconditioning. Interestingly, the adaptations that occur during spaceflight are often opposite of chronic terrestrial exercise, which is one reason that regular exercise remains a crucial countermeasure for every astronaut. Despite this natural synergy between exercise and space physiology, we are unaware of any substantial effort to incorporate space physiology into an exercise physiology curriculum. We encourage such practice, especially toward the end of the semester. It provides a needed change of pace for both students and instructor at a time when students are looking ahead to the end of the semester. Without even realizing it, the students are engaged in a novel curriculum that reinforces key exercise physiology concepts learned earlier in the semester.

ACKNOWLEDGMENTS

The authors thank Huan Yang for assistance with the figures. J. R. Carter also acknowledges Dr. William Cooke, whose mentorship and graduate course entitled “Aerospace Physiology” inspired this curriculum.

GRANTS

This work was supported by a Teaching Career Enhancement Award from the American Physiological Society.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: J.R.C. conception and design of research; J.R.C. and J.B.W. interpreted results of experiments; J.R.C. prepared figures; J.R.C. drafted manuscript; J.R.C. and J.B.W. edited and revised manuscript; J.R.C. and J.B.W. approved final version of manuscript.

REFERENCES