Teaching effectiveness is enhanced by generating student enthusiasm, by using active learning techniques, and by convincing students of the value of acquiring knowledge in the area of study. We have employed a technique to teach physiology to bioengineering students that couples students' enthusiasm for their chosen field, bioengineering, with an active learning process in which students are asked to design a biomedical device to enhance, replace, or create a new cellular or organ system function. Each assignment is designed with specific constraints that serve to direct students' attention to specific areas of study and that require students to create original designs. Preventing students from using existing designs spurred student invention and enthusiasm for the projects. Students were divided into groups or "design discovery teams" as might be done in a biomedical device industry setting. Students then researched the physiological issues that would need to be addressed to produce an acceptable design. Groups met with faculty to brainstorm and to obtain approval for their general design concepts before proceeding. Students then presented their designs to the instructors in a structured, written outline form and to the class as a 10-minute oral presentation. Grades were based on the outline, oral presentation, and peer evaluations (group members anonymously rated contributions of other members of their team). We believe that this approach succeeded in generating enthusiasm for learning physiology by allowing the students to think creatively in their chosen field of study and that it has resulted in students developing a more thorough understanding of difficult physiological concepts than would have been achieved with a traditional didactic lecture approach.


Key words: peer evaluation; active learning; collaborative learning

Physiology is most often taught to undergraduate students in a didactic lecture style employing a "systems approach" in which each organ system is addressed in succession and, to some extent, in isolation. Traditionally, cellular physiology and the physics and chemistry essential for understanding physiological concepts are presented first. This unit is generally followed by the study of excitable cells in general, followed by the study of nerve cells and the nervous system in particular. Muscle physiology is usually next, followed by the remaining organ systems (cardiovascular, respiratory, renal, gastrointestinal, endocrine, and reproductive systems). Whereas this is a logical and time-proven method of teaching physiology, it has the drawback of being a totally passive approach to the learning process by which an instruc-
tor delivers a body of knowledge to a student. Active learning processes like the collaborative learning process that we describe here have been reported to be more effective than lectures in engaging students in analysis, evaluation, and synthesis (higher-order thinking) (1, 2, 4). A conventional lecture approach also makes it difficult to impress on naive students the “integrative” nature of physiology, i.e., that organ systems, although taught as isolated units, in fact work together in a complex, coordinated manner to maintain biological homeostasis. An additional problem is that, in many instances, this body of knowledge is presented as fixed, complete, and unchanging. This gives students an incorrect impression of the field as static, whereas, in actuality, it is a rapidly evolving discipline in which the conventional dogma changes daily. A final drawback is that instructors are often unable to generate real student enthusiasm for learning physiological concepts via a straight didactic treatment of the material. Generating student enthusiasm has proven to be effective in enhancing learning (1). A semester (or two) of nothing but “transfer of information”-style lecturing is, more often than not, uninspiring for both the instructors and those they are trying to instruct.

Teaching physiology to bioengineering students presents the instructor with learning obstacles and opportunities somewhat different from those faced when teaching students from other, more traditional life science disciplines (preprofessional, pre-allied health, biology, or zoology). Undergraduate bioengineering students usually have weak biology and chemistry backgrounds compared with students preparing for health-related professional schools and often are less than fully convinced of the necessity for acquiring an excellent grounding in physiology. On the other hand, these students are bright, very enthusiastic about their chosen field, and have strong mathematics and physics backgrounds. Given these considerations, we decided that the conventional didactic lecture approach to teaching biomedical engineering students was less than optimal. We wanted to create a teaching process that would provide bioengineering students with the necessary link between what we wanted them to learn about our discipline and their own expectations and interests as engineers. We also were made aware that our colleagues on the bioengineering faculty were receiving feedback from the biotechnology industry to the effect that students were coming to work for them with virtually no experience in working in groups (industry effectively uses teams to tackle assignments and specific problems) (5). The standard lecture approach simply does not provide sufficient opportunities for students to work together and brainstorm ideas. Perhaps more importantly, approaches in which students work in teams to learn collaboratively have proven more effective in enhancing learning compared with conventional lectures (1, 4).

We therefore elected to impose on the traditional structure a method that allows students to learn actively and to think creatively by requiring them to address novel medical device design problems. Students were asked to work in groups, resulting in a collaborative problem-solving and learning environment. This has proven effective in motivating our students to ask questions, to learn independently the necessary fundamentals, and to begin to apply creative thinking within a physiological context. Requiring students to design a solution to an unsolved problem helps to distinguish the assignment from a library research project and frees the student to think more creatively. We call this method the “design discovery team approach.”

**OVERALL STRUCTURE OF COURSE**

Our course is made up of three components: 1) a laboratory, which provides students with an introduction to the collection of physiological measurements and includes exercises to enhance an understanding of basic physiological concepts along with instruction in anatomy, utilizing computer software; 2) didactic lectures structured around the reading assignments from the assigned text (the subject content of the didactic lectures parallels the subject areas of the third component); and 3) design discovery assignments, for which students are assigned to teams and must work together to design (on paper) an artificial device that will augment, replace, or create a new cellular or organ system function. In our course, team members stay together throughout the semester and all teams receive the same assignment. Each device design assignment counts for between 7.5 and 15% of a student’s total grade in the course. Competition between groups is promoted by informing the students that faculty will identify the group producing the most
innovative and well-thought-out design. At the conclusion of each project period, we hold an in-class “awards” ceremony for this winning team, including music (e.g., Beethoven’s “Ode to Joy” or Queen’s “We are the Champions”), and give each student a prize (usually plastic pocket protectors, something engineering students love). Although this may seem a little over the top to some of our colleagues, we have found that a minimal investment in class time results in a very large increase in enthusiasm and esprit de corps within the groups. Not only do the students want to perform well in terms of the assignment grade, they also want to win, stand in front of their classmates, and receive their applause. We hasten to add that in our experience thus far, we have yet to encounter any problems with intellectual dishonesty, and none of our students have treated each other with anything less than an appropriate degree of professional respect. Instructors using our approach, however, must be careful to ensure that the degree of competitiveness generated by the projects remains constructive. We typically assign three design projects per semester, a number that our students also find reasonable (based on student responses to an end-of-course evaluation on the device design method).

This course is the first of a two-semester sequence. First-semester subject coverage includes basic cellular, nervous system, muscle, and cardiovascular physiology, with the rest of the organ systems being covered in the second semester. An important point to be made is that design assignments are made at the beginning of the related unit. Therefore, design considerations must begin well before students have heard lectures over the pertinent areas of physiology. Students must read and learn on their own ahead of the lectures to begin their designs. In addition, our assignments often require students to learn about organ systems not covered during the semester. Our expectation that students must read and learn outside of what is being covered in class is made clear to the students at the beginning of the course. Students quickly realize that they must consider novel information about other organ systems and must integrate this self-acquired knowledge into the plans for their device. Therefore, design assignments serve to promote reading and study independent of lectures, resulting in, we believe, students that are ultimately more advanced in their understanding of physiology than they would be if taught by a didactic methodology alone, both in terms of absolute “factual” knowledge of how the body works and, more importantly, in their appreciation of the interrelatedness of the body’s homeostatic control processes across multiple organ systems.

GOALS OF THE DESIGN DISCOVERY TEAM APPROACH AND ASSIGNMENT CRITERIA

Our major goals in creating the design discovery team approach assignments are to encourage active learning, creativity, team work, and enthusiasm.

Active learning. Students must work collaboratively to develop solutions to the assigned physiological problems. The design assignments are complex and require students to integrate knowledge gained about the component parts of physiology to find a functional solution. Student designs invariably create new physiological problems that require further consideration of the design. Only by considering the interactions of the organ systems and the collection of control systems regulating these interactions is it possible to develop a working understanding of how the human body works. As the students begin the brainstorming sessions needed to complete the assignments, they bring their initial ideas to us for comment and direction. We then provide some limited guidance. In some cases, we found that students met with us with the intention to acquire our ideas rather than to discuss their own. Too much guidance had served to encourage these students to be even more dependent. Therefore, over time, we have found ourselves becoming more reserved with specific design suggestions. In these meetings we often make the point that if they were to apply their planned approach, some problems would be solved but others would arise because of the nature of their design. In other words, potential solutions will invariably create new problems and the key to good design is to maximize the utility of the finished device while minimizing the hazards it creates. This intellectual balancing act has proven to be an important benefit to learning provided by this approach and is another example of an exercise that these students had never before had the opportunity to experience. Some students realize the utility (and inevitability) of this balancing act and come to appreciate it, whereas others do become somewhat frustrated. Nevertheless, we deliberately foster this aspect...
of the approach because it forces students to move from their naive concept that there is an “ideal” or “perfect” or “correct” solution to a problem to the more advanced perspective of finding an “optimal” solution. Students are forced to make some tough choices in their design decisions and to have ready adequate explanations for the decisions they have made and for the problems those decisions might cause.

Creativity. Students are given problems to solve that have no published solutions. In fact, these problems, more often than not, are not solvable with existing technology. This was a deliberate decision on our part and derives from our belief that our students would be more enthusiastic about working on problems for which there was no device already on the market. We also wanted to avoid the possibility that students would find a ready-made solution in the literature or on the World Wide Web and present that as their design project (whether fully attributed or not). Whereas solutions must strictly adhere to physiological realities, we give our students liberty to propose new technologies. However, they must be able to rationally explain how the proposed technologies would function. Initially, we did not make it sufficiently clear that although they could conceptualize and employ technologies that do not yet exist, they would have to adequately describe a plausible theoretical design and function for such technology. This resulted in some students employing technical wizardry that lacked credibility, but the problem was resolved in subsequent project assignments with clarification. We require that the students rigorously abide by the functional requirements of living systems. For example, we had no objection to a design team utilizing a tiny nuclear reactor as a long-term energy source for an implantable device. However, they then had to take into account the heat generated by such a device (and any noxious waste products) and make sure that they did not heat cells or tissues above what we know to be their tolerable limits. This restriction serves an additional heuristic purpose because it reinforces the students’ understanding and appreciation of both the amazing toughness and durability of living systems as well as what the limits on that toughness might be (in terms of physical stress, temperature, acid-base conditions, etc.). We were able to use this set of project constraints to emphasize what is probably the principle and unifying concept in modern physiology, homeostasis. The students’ device must solve or ameliorate the imposed defect and must also not interfere with normal homeostatic regulation.

Function within a team. A large fraction of this particular cohort of students is headed for employment with biotechnology firms. Industry commonly employs a team approach to problem solving and, therefore, the ability to work cooperatively in groups is a skill that has practical value. Our students appreciate this point and enjoy the opportunity to practice this skill for future application in the “real world.” Additionally, collaborative problem solving provides students with an active learning experience. When asked in our course evaluation whether the students preferred to remain in the same teams for all three projects or not, the overwhelming majority felt that working with the same group members throughout the semester was preferable in that it allowed them to evolve a “team affect” that maximized the particular skills of the various members.

Enthusiasm for learning and for the bioengineering field. The design assignments address important medical problems with no existing effective solutions. The assignments are designed so that students will consider solutions beyond the existing frontiers of their field. We have reasoned that our students will be more likely to rise to the challenge of designing an imaginative and effective prosthesis if they know that a successful design might represent a potential “first-to-market” solution to an important medical problem. Again, we try to link the students’ design team experience with their expectations of the postgraduate workplace. Encouraging the students to consider these types of solutions fosters enthusiasm for the discipline because it encourages students to consider designs that would represent significant advances in the field of bioengineering.

STRUCTURE OF ASSIGNMENT

What we provide the students. Our course syllabus includes a general description of the device design projects that delineates what we expect from the students in terms of a written and oral report (see APPENDIX A). We explain that our grading system
includes a peer evaluation in which each group member anonymously evaluates the contribution to the project of each teammate. We also indicate to the students that we want them to place the emphasis of their project designs on the physiology involved rather than on the engineering details. We are fairly scrupulous in our written explanation of what we expect from the students on these projects and how they will be evaluated. Unlike a conventional, short-answer-style examination in physiology, our grading of the device design projects must, by its very nature, be somewhat subjective. These particular students have limited experience with nonobjective examinations, and we try to make it as clear as possible how they will be evaluated. We also want to assure the students that we will be able to evaluate their projects fairly. This care in defining the grading criteria and the assurance of fairness has been successful in maintaining a cooperative relationship between the students and instructors regarding the projects. A final point here is that we believe that the fact that the grading of projects is necessarily subjective is not in and of itself a bad thing. Our students will have to face subjective (as well as objective) evaluation of their ideas and work once they leave the engineering college and enter industry. Practical experience in being evaluated in this subjective and somewhat holistic manner will improve our students’ ability to accept, interpret, and learn from this type of evaluation in the future.

We next provide the students with a specific project description that lays out for them the type of device that they must design (see examples in Appendix B). Most projects are designed to remedy a specific pathological condition. Our collective experience with a wide variety of physiology students (undergraduate life science majors, pre-allied health undergraduates, medical and veterinary students, and graduate students in physiology) has taught us that few things in the life sciences captivate a student as much as disease. There is an almost morbid fascination with dysfunction that can be used creatively to teach the physiology that underlies the disease condition. Also, in the particular case of bioengineering students, we are able to make the additional argument that it is highly likely that they will be called on to work on devices and techniques designed to improve specific disease conditions. This link to the real world further enhances the appeal of the project. Other project assignments involve devices that extend normal function (for example, a device to allow persons to live and work at altitude without supplemental oxygen). We believe that a successful assignment is one that requires all groups in the class to approach the same general problem but that provides for a number of different potential solutions. This is important because the weighing of the different approaches by the groups is an important part of the learning process. We endeavor to have some differences in the designs arrived at by the different groups (so that groups work independently of one another) and to minimize repetition during the oral presentations.

What the students submit to us. The project is presented to the instructors as a structured outline (see Appendixes A and D) and to the class as an oral presentation (most groups utilize the PowerPoint presentation software package). The components of both the written and oral presentation include 1) a description of the assignment and the physiological problems that must be overcome; 2) a discussion of the potential approaches to overcoming the problem; 3) a description of the approach to be taken, including device design and a description of how the device is controlled; 4) physiological problems that might be created by utilizing this approach; and 5) a rational comparison of the theoretical performance of the device and the natural organ or structure that it replaces or augments.

Grading. Projects are graded on the basis of a clearly defined weighting of the components of the structured outline (45%) and the oral presentation (35%). These grades are the same for all project members. The final component of the grade is a peer evaluation (Appendix C). At the end of each project, each student completes a scoring sheet for each of the other team members. Criteria include attendance at group meetings, contribution to group meetings, contribution to the project concept, library work, and contribution to the oral presentation. Our initial weighting of the peer component was 10% of each project grade. However, we found that this did not provide sufficient incentive for all students (although only a small number were poorly reviewed by their peers). We have since increased this value to 20% of the grade. Overall, the projects account for 30% of the grade for the class, the laboratory accounts for 25%, and the balance is from...
examinations covering the reading assignments and didactic material.

EXAMPLES OF DEVICE DESIGN ASSIGNMENTS
AND SELECTED STUDENT RESPONSES

See APPENDIX B for detailed descriptions of specific projects as handed out to the students.

Biomembrane stabilizer nanomachine. We begin the course with lectures on cell physiology and physiological chemistry, and we have, therefore, elected for the past four years to link the first design project to this unit by requiring the students to design a nanomachine to replace or repair some cell level dysfunction. For example, one year we asked the students to design a nanomachine that would function to maintain and stabilize a cell’s membrane potential. We received a diverse set of creative responses to this assignment. One group designed a nanomachine that would attach itself to the cell membrane and then influence the temperature locally at the site of Na-K-ATPase pumps. The pumps are enzymatic, and an appropriate increase in temperature would increase the reaction rate and thus the net movement of positively charged ions out of the cell to increase cell polarity. This design suffered from some flaws of practicality such as the large number of devices that would be necessary to influence sufficient Na-K-ATPase pumps to accomplish the tasks. However, the group recognized this problem and included a discussion of this shortcoming in their presentation. What is more important to recognize from the standpoint of teaching is the elegance and sophistication of this approach, given the level of training of the students, as evidence of the success of the method as a means of teaching physiology.

Mars mission microgravity cardiac enhancement device. This project was linked to the cardiovascular physiology unit and was designed to force the students to consider multiple organ system integration. We asked the students to design a fully implantable prosthesis that would prevent the development of orthostatic hypotension in Mars mission astronauts when they descend to the Martian surface and on their return to Earth. We stipulated that there could be no direct control of the artificial cardiomyocytes by the central nervous system. We then asked the groups to figure out a way to use multiples of their cardiac cell devices to completely replace a failing human heart. One team came up with a synthetic polymer that was designed
so that the application of an electrical charge resulted in a reversible change in hydrophobicity characteristics and contraction of the polymer (Appendix D). The theoretical performance of this material was such that it could contract to one-half its original hydrated length and could create forces sufficient to lift 1,000 times its dry weight. The polymer was then molded into cell units and cross-linked. The contractile units were fashioned into ellipsoid contractile units and assembled into an artificial heart containing artificial valves and Teflon vascular connections. An implantable power supply and microchip then controlled contractions to recreate a cardiac cycle like that of a normal heart. The strength of this design is the very elegant and highly biological application of a bioengineered contractile protein. This design suffered from the flaw that it did not clearly show how the internal surfaces of the chambers would contract to result in a smaller internal volume to generate the normal cardiac pressures. However, the lack of clarity in this area of the design was identified and recognized during the postpresentation discussion, and this design weakness, we felt, provided us with an excellent opportunity to explore cardiac hemodynamics from a new and interesting perspective.

**DISCUSSION**

The design projects resulted in a more enthusiastic learning environment. Students developed a far more penetrating understanding of physiology in the subject areas related to the projects and, in many instances, extended their knowledge of other areas of physiology by active learning, entirely on their own. This became very evident during discussion periods with students during both the preparation of the projects and the question period that followed each presentation. It is important to stress that neither of us are engineers, bio- or otherwise, and that, in our experience, this did not prove to be a hindrance in applying the device discovery team technique. We also believe that whereas we were able to use this method to teach physiology to bioengineering undergraduates, it seems likely that a similar model could be used for nonengineering students as well. Minimal difficulties were encountered with the grading methods, and those that did occur were mitigated by the care exercised in the presentation of the grading criteria. Minimal difficulties were encountered because students worked in teams. There were some complaints that individual team members did not contribute yet received the same grade, but we believe that this problem was largely mitigated by the peer evaluation component of the grade. Although peer evaluation is a technique that might result in group disharmony, we believe that careful design of the assessment instrument, discussions with the students about the process, and timely management of individual group/student concerns result in minimal risk and significant reward. Others have reported that peer evaluation can positively impact on the collaborative learning process (3, 6). Student evaluations of the device design discovery projects were almost unanimously positive (Appendix E). This was the first team-focused, active learning experience for most of these students, and, for the most part, they worked hard and performed well.

In almost every group, there exists a range of abilities among its members. Therefore, the potential exists for stronger contributors to resent or be frustrated with weaker contributors and vice versa. However, we found that promoting team building was effective in maintaining an atmosphere of common mission within groups, resulting in minimal disharmony. Our impression is supported by others who found that certain group inhomogeneities (the deliberate inclusion of stronger and weaker students within a group) could even enhance the experience (6).

Significant effort is required in creating the design assignments; failure to create an effective assignment will result in the class arriving at simplistic and uniform solutions, resulting in a loss of learning opportunity and tedium for the audience during the presentations. These projects required faculty to provide time to meet with students out of class. Although meeting and brainstorming with students was likely one of the most educationally constructive aspects of the approach, it should be understood that this requires an additional time commitment on the part of faculty. Finally, students stated that they worked very hard on the projects, and some felt that this effort might have reduced time available for examination preparation and, consequently, performance on the class examinations. We believe that this negative, or perceived negative, aspect was far outweighed by the effective learning opportunity provided by the design discovery team approach.
Our approach has been to reduce the time spent and content delivered to students through conventional lectures to provide time for student presentations and discussion. Others have found that collaborative learning techniques are as efficient as lectures in terms of retention of content material and superior to lectures in terms of promoting student higher-order thinking, suggesting that, if anything, efficiency is gained rather than lost by our approach (1). In fact, we find ourselves incrementally (old habits die hard) reducing the time dedicated to lectures year by year. Although we feel that there is a place for both lectures and collaborative learning, we also feel that our results are increasingly better with each increase in the collaborative learning component of the course.

APPENDIX A: GENERAL GROUP PROJECT INFORMATION

We will divide the class into six groups of six to seven students each (we reserve the right to reorganize group personnel at any point in the semester at our discretion). Each group will constitute a “bioengineering device discovery team” and will be responsible for the design of three physiological prosthetic devices over the course of the semester. All of the groups will be assigned the same design problem and will be required to produce competing designs over a 2–4 week period (Projects 1 and 2) or over a 5-week period (Project 3). You must have your preliminary design concept approved by us before you work out the details of the project. You will then be required to give a 10-minute-long group presentation (with illustrations) on your design. Time will be kept and you must finish within the allotted 10-minute period. The exact format of the oral group presentations may vary from assignment to assignment (e.g., initial conceptual design, mechanical engineering, electrical engineering, materials research, illustrations/graphics/computer animations, etc.) and 2) which group members will be presenting and specifically which aspects of the presentation will be covered by which member. All group members must have presented orally at least once by the end of the semester. It is up to your group how to organize the presentation. You can have one person present or the entire group. We recommend that you consider having 2–3 members deliver your presentation and rotate who does what over the three projects. Your group will be expected to field questions from your instructors and classmates following your presentation. The order of the group presentations for the first assignment will be determined by lottery. The order of the presentations for the remaining assignments will be rotated. The presentations will be videotaped so that students who wish to review their presentations and improve their public speaking skills may do so.

Grading

We will assign group project grades based on how well your group addresses the five critical points listed above. The written outline will count for 45% of your project grade, the oral presentation for 35%, and peer evaluations by your fellow group members for 20% (we will distribute a peer evaluation form prior to each presentation). All group members will receive the same project outline and oral presentation grade. Collectively, the three group projects will make up 30% of your total grade in this course.

For each project, we will decide on a winning design and the winning design team will receive a handsome trophy and other prizes.1

Note: We want you to place the emphasis in your project designs on the physiology involved rather than on the engineering details. In other words, you are permitted to take some liberties with the engineering aspects of the design (e.g., you can describe and use materials that exist only in your imaginations). However, for any futuristic designs or materials that you employ, you must be able to provide a rational explanation of how they will be built and how.

1 The authors are “Trekkies.” Therefore, we chose as a traveling trophy a model of the starship Enterprise to which we apply brass plates depicting the title of the current project and the winning group. This trophy is then placed in a display case located in a popular student study area. We also provide each member of the winning team a plastic pocket protector, a prize emblematic of their chosen field of bioengineering.
they will work. You must stay within the realm of the real world in terms of the physiology involved.

APPENDIX B: SELECTED DEVICE DESIGN PROJECT ASSIGNMENTS

Biomembrane Stabilizer Nanomachine

All plasma membranes (the biological membranes that separate the inside of a cell or organelle from the outside) have a membrane potential, i.e., they are polarized electrically. Proper maintenance of the membrane potential is vital for a cell to survive and to function properly. Various pathological conditions can result in dysfunctions in cell membrane potential with extremely serious consequences, including death. It has also been suggested by some researchers that the normal aging process in mammals is associated with a gradual alteration (depolarization) of cell membranes throughout the body.

You are to design a cellular nanomachine whose function is to maintain and stabilize a cell’s membrane potential. Nanomachines (as the name implies) are extremely small devices and your machine must be of a scale appropriate to its function as a cell membrane potential stabilizer. You may design the nanodevice to function within the cell or to remain outside the cell. It’s up to you. If your machine works from inside the cell, you must come up with a mechanism to get the device into the intracellular compartment (inside the cell). If it works from outside, you must describe how it will exert its effects on cell membrane potential. You may accept as a given that your device can be injected into an animal (human or otherwise) and will arrive safely outside the target cell. From that point on— it’s up to you.

Remember, there are a variety of ways your nanomachine could work and many of these are equally good. Consider how a cell regulates its own membrane potential. Think about these processes and design your machine to mimic some of them. Try and keep the design as simple as possible— use your imaginations but ground what you do in biological reality.

Good luck, and make it so!

Mars Mission Microgravity Cardiac Enhancement Device

“Space, the final frontier!”

The recent report by National Aeronautics and Space Administration (NASA) of the apparent presence of microbial life forms in asteroids of Martian origin has prompted the United States government and NASA to seriously rethink their plans for a manned mission to the Red Planet. Current plans call for a six-month voyage to Mars aboard a space shuttle-like spacecraft, followed by three weeks of manned exploratory work on the planet’s surface. The astronauts would then take another six months to return to Earth. During takeoff and landing, the astronauts will be exposed to hypergravity conditions (up to 1.2 G, i.e., 1.2 times the Earth’s normal gravitational field), and during the transit periods, they will be at essentially zero G (microgravity). Space bioscientists have known since the beginning of manned space flights in the 1960s that there are a number of serious physiological problems that develop in humans in response to exposure to microgravity. After even a fairly short space mission (several days), astronauts experience a phenomenon called orthostatic hypotension on their return to Earth. During an orthostatic hypotension event, blood pressure falls, resulting in a decrease in cardiac output and consequently brain blood flow. The subject feels dizzy and can experience syncope (they lose consciousness). In general, astronauts do not get up and walk out of the shuttle cabin after landing, rather they are assisted or carried off on stretchers. NASA is naturally unhappy with this state of affairs for both public relations reasons and for the more important reason that they would like their crews to be able to get up and get out of the spacecraft in the event of a postlanding emergency. For the Mars mission there is an additional consideration. Episodes of orthostatic hypotension can continue for several days after returning to a higher gravitational field, and NASA would like the Mars astronauts to begin their work on the surface immediately after landing.

During exposure to microgravity, astronauts initially experience a redistribution of blood volume in their bodies. On Earth, blood tends to pool in the veins (capacitance vessels) of the lower extremities due to the effects of gravity. In space, blood redistributes to the great veins of the chest and head (central venous blood volume expansion). After several days in microgravity, homeostatic mechanisms result in a reduction in total body water and hence blood volume via an increase in water loss by diuresis and evaporation and a suppression of the thirst drive, which partially compensates for the excess blood in the chest and head. Our Mars astronauts will thus be hypovolemic (lower than normal blood volume) during their transit periods. On their return to a planetary gravitational field like that on Mars (0.8 G) or Earth (1.0 G) their blood again tends to pool in their lower legs, but because their overall blood volumes are now low, they experience an insufficient return of blood to the heart (venous return is compromised) and a consequent drop in blood pressure and reduction in brain blood flow. Over the course of several days to a few weeks, blood volume is restored to normal and orthostatic hypotension ceases to be a problem.

Your bioengineering firm has won the contract from NASA to design a fully implantable prosthesis that will prevent the development of orthostatic hypotension in the Mars mission astronauts when they descend to the Martian surface and, six months later, when they return to Earth. The astronauts have to be able to do heavy work immediately after landing (no acclimatization time) and they must be able to walk off the Mars shuttle on their own power at the end of the mission. Your company’s research and development people have already ruled out the use of such methods as: 1) Oral rehydration therapy (i.e., drinking 1–2 liters of isotonic solution just prior to landing). This is the current therapy [NASA calls this the rehydration “countermeasure” and it actually only works for short stays in microgravity (less than 7 days)]. 2) Intravenous administration of fluids. It is difficult and dangerous to put in an intravenous line and volume expand while in orbit. 3) No pharmacological interventions. You cannot just administer cardioactive or vasoactive
drugs. Human responses to drugs administered while in microgravity could be very different from the responses seen back on Earth and, of course, in space, you are a long way from the emergency room if you do have a serious adverse response.

You have the option of designing a device that, once implanted, will function for the duration of a 13- to 24-month mission and can then be removed surgically once back on Earth or you can design a permanent device. Remember, your prosthesis must not result in physiological dysfunctions once the astronauts have returned to Earth and reacclimated to 1.0 G.

Good luck, and make it so!

**Artificial Cardiac Muscle Fiber/Composite Artificial “Heart”**

This is a two-part design project. First, you are to design an artificial cardiac muscle fiber (i.e., an artificial, single, cardiac muscle cell or ACM). You may design your ACM to be of similar size to a natural muscle fiber or you may make it larger—the choice is yours. However, be sure to carefully consider the dimensions of your device and the pros and cons of your engineering decisions. The ACM must behave like a natural cardiac muscle fiber, that is to say, it must contract and relax in a controlled manner via some sort of “sliding filament” system. Your design must include a careful description of the control mechanism(s) that will govern contraction and relaxation in your ACM. You must take as a given that there can be no direct control of the ACMs by the central nervous system.

Second, you must figure out a way to use multiples of your ACM devices to completely replace a failing human heart. You must assume that the patient’s ventricles (the main pumping chambers of the heart) are terminally dysfunctional. The job of the heart, of course, is to pump blood to both the lungs (for oxygenation) and to the rest of the body. The flow of blood from the heart is pulsatile rather than continuous, i.e., at some times during the cardiac cycle there is blood flow and at other times there is no flow. The blood vessels and control systems of the body are adapted for pulsatile flow, so some consideration of this fact must be made in your design. You will need to research how much blood must be pumped per minute for your patient to lead a reasonably normal life and you must then figure out a way to use the ACMs to accomplish this pumping function. You may use the ACMs to directly replace the diseased heart (i.e., construct an artificial, central pumping organ) or alternatively, you may choose not to replace the heart itself but to distribute the ACM devices throughout the vascular (blood vessel) system in some manner. For example, most annelids (worms) do not have a single pump but rather have several “hearts” placed in series in one of their major blood vessels. There may be some excellent engineering reasons for adopting a “noncentral” strategy to solve this particular bioengineering problem. The choice is yours, but in either case you must completely describe and defend your decisions. In previous projects we have allowed you a lot of leeway on exactly how you will place your devices in the body. This time around you must provide us with a clear description of how you will implant your device(s). We will evaluate the relative feasibility of your implantation strategies as part of our review of your designs.

We suggest you divide your design team into two subgroups for this project. The first group should immediately begin to work on the ACM design with advice and consultation from the rest of the team engineers. As soon as a reasonable model for the ACM has been developed (even if this is not the finished version of the ACM), the second subgroup should commence work on the composite artificial “heart” problem.

Good luck, and make it so!

### APPENDIX C: PHYSIOLOGY FOR BIOENGINEERING MAJORS VTPP 334

**Design Discovery Team Member Evaluation Form**

Team: __________________________

Name of evaluator: __________________________

Instructions: Score each of your team members from 0–5 on each category below (5 is best and 0 is worst and you are not restricted to using whole numbers). If a team member was, by group consensus, held not responsible for categories 4, 5, or 6 for this particular project, then answer NA (categories marked NA will not count toward calculating a mean score). The value of this grade is 20% of the project grade. Individual scores will not be disclosed to the other students.

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**VOLUME 22 : NUMBER 1 – ADVANCES IN PHYSIOLOGY EDUCATION – DECEMBER 1999**
APPENDIX D: TEAM GAMMA PHYSIOLOGY 334  
SECTION 501

Artificial Cardiac Muscle Fiber/Composite  
Artificial “Heart”

I. Basis for our design  
A. Study by Dan W. Urry at University of Alabama at Birmingham  
1. Synthetic polymers that become more ordered when temperatures rise  
   a. Start in extended state, then fold into a helix  
   b. Similar to elastin in normal bodies  
   c. Hydrophobic and hydrophilic parts  
   d. Contract to up to 1/2 their swollen length and lift 1,000 times their dry weight  
2. Limitless variations to polymer design for specific needs are possible  
   a. Change particular amino acids  
   b. Stimulus can also be varied (temperature, electricity, etc.)

II. Contractile protein  
A. Based on above research  
B. Basic unit of elastin is poly(VPGVG)  
C. More order at higher temperatures  
   1. Entropy increase with increased temperature (inverse temperature transition)  
   2. Occurs at a specific temperature $T_t$  
D. Mechanism involves interaction with aqueous environment  
   1. Low temperature water forms hydrogen bonds  
      a. Organized pentamer structure of water  
      b. Prevents folding of protein  
   2. High temperature water is bulk fluid  
      a. No organized structure of water thus protein is free to fold  
      b. Entropy of water raised by more than reduction for protein  
   3. Interaction depends on hydrophobic groups  
      a. Hydrophobic groups allow formation of pentamer  
      b. Hydrophobic groups lower $T_t$  
E. Rather than change temperature we can change hydrophobicity  
   1. Prosthetic group that can be reversibly changed is attached  
   2. Change in hydrophobicity results in $\Delta T_t$  
   3. Contraction results when $T_t$ is below ambient temperature  
F. Cysteine (amino acid) can change its hydrophobicity  
   1. Cysteine easily reduced (accept electron) becoming more hydrophobic  
   2. Contracts in response to negative electric current

III. Manufactured through practice of Solution and Solid-Phase Peptide Synthesis  
A. Organized into cells of any shape  
B. Current is insulated from rest of body

IV. Artificial Heart  
A. Size  
   1. Normal adult heart (about 8 cm wide and 12 cm long)  
   2. Mechanical heart is 4 cm in max. radius and 12 cm long

B. Shape  
   1. Based on two half ellipsoids joined together  
   a. $f(x, y) = -8 \left(1 - \left(\frac{x^2}{4}\right)^2 - \left(\frac{y^2}{4}\right)^2\right)^2 + 8$  
   b. $f(x, y) = 4\left(1 - \left(\frac{x^2}{4}\right)^2 - \left(\frac{y^2}{4}\right)^2\right)^2 + 8$  
   2. Shape encloses 402-ml volume  
C. Septa divide artificial heart  
   1. Central septa divides heart in two, each of these halves are divided into two  
   2. Four compartments  
      a. Inner two are “ventricles”  
      b. Outer two are “atria”

D. Outer two septa lie .69° radius from any cross section of the ellipses  
   1. Refer to diagram for more detailed mathematical explanation  
      a. Allows two 151-ml ventricles  
      b. Fiber must contract 46% to yield a 70-ml ventricular volume change

E. Motion  
   1. As fibers contract up to 46%, the outer septa move inward toward the middle, forcing out 70 ml of blood

F. Fiber location (see diagram)  
   1. Fibers arranged horizontally  
   2. Fibers controlled in groups  
      a. 4 vertical bands are independently controlled but coordinated  
      b. Fibers anchored between edge of each septum  
      c. Fibers are horizontally differentiated: superior portions of atria contract first, inferior portions of ventricles contract first

G. Valves (see diagram)  
   1. Valves in atrial/ventricular septa form atrioventricular (AV) valves  
   2. Valves at top of ventricles open to aorta or pulmonary artery

V. Materials  
A. Blood vessels  
   1. Teflon has a long history as an artificial blood vessel implant  
   2. Works well on large diameter vessels  
      a. Pulmonary artery and veins  
      b. Superior and inferior vena cava  
      c. Aorta

B. Inner lining of heart  
   1. Extracellular matrix proteins such as fibronectin and laminin promote endothelial cells binding to different surfaces (inner heart surfaces)  
   2. Septum made of collagen mesh used for attraction of endothelial cells  
   3. Endothelial lining reduces friction, clotting and promotes laminar flow

C. Artificial heart will be enclosed by a pseudopericardial sac composed of pericardial cells on a collagen mesh

D. Valves  
   1. AV valves and pulmonary valves will be artificial heart valve 153M:Jonescu-Shiley 3M Pericardial  
   2. This valve has been proven effective under various environments
E. Power source
   1. Power received via transdermal induction coil from outside battery

VI. Cardiac cycle
   A. Input-sensing devices
      1. Blood pressure monitoring devices placed in left ventricle
         a. Aid in determining cardiac cycle and force of contraction
            (120 mmHg/80 mmHg)
         b. Pressure falls heart beats harder
      2. Blood pH will be monitored in pulmonary artery to determine O2 levels
         a. Help determine needed rate of heart contraction
         b. Low pH, more O2 needed, heart will be stimulated to beat faster
   B. Electrical stimulation will be regulated by the above factors and controlled by CPU
   C. Blood flow (see diagram)
      1. End of diastole, atria contract from top down, forcing 70 ml into each ventricle through AV valves, pulmonary and aortic valves are closed
      2. At systole, atria relax, ventricles contract from bottom up, forcing blood through pulmonary artery and aorta (AV valves shut due to DP).

VII. Implementation procedures
   A. Standard “median sternotomy” procedure
   B. Prevent clotting by using heparin during surgery
   C. Cardiectomy is performed as a for a primary cardiac transplant patient

VIII. Physiological problems
Complications of artificial heart implementation include: hemorrhaging, thromboembolism, sepsis, multisystem failure, device-related failure (valve failure, etc.)

APPENDIX E: SELECTED STUDENT COMMENTS ON DEVICE DESIGN PROJECTS

Students responded anonymously to the question, “Did you feel that the concept of the device design projects strengthened your understanding and appreciation of physiological processes?”

“Yes, because instead of requiring just a regurgitation of knowledge, they required the application of knowledge which led to a more in depth understanding.”

“Yes; trying to synthetically reproduce/correct what the body does naturally required thorough understanding of the process and actually made us aware of how specialized and functional the physiological design of the body is.”

“Yes. Design projects not only increased my understanding of physiological processes, it allowed me to work under conditions (cooperating with other people, managing time, researching new information) that would be similar to working as a bioengineer.”

“Yes, these projects were a very good idea. They were definitely a challenge but it was well worth it. Not only did it give us a greater understanding of the concepts but it also challenged us to work together with a group—something that is very impressive.”

“The device design projects were an excellent idea. They helped me explore my creativity and cooperative group skills. I think that working in a group allowed me to accept the concept of group decisions over individual decisions. In trying to unravel the complexities of the design projects’ physiological problems, I became more aware of certain processes and details.”

“Yes—I feel that the projects allowed us to apply physiology to engineering. We were able to see what it would be like to work on a design while at the same time improving our comprehension of the material.”

“This has been one of the most exciting things I’ve done in college, and at the same time one of the most stressful. I would enjoy spending more time on the device projects.”

“I feel the device design projects helped me to apply and retain what we discussed in class, as well as give me valuable experience for the future.”

“I think that the design projects really helped my understanding. We had to research more in depth for information, and that helped (although it took much time outside of class).”

“Yes, and by restricting the solutions to solutions which have not been enacted before, it forces the students to be more imaginative.”

“No, the projects should have been based more on reality than they were. It was difficult to find information on many of the topics we were researching due to the fact that, because most of these problems have never occurred, no research has been done. Too much of the problem was left up to speculation which usually led to you criticizing our ideas.”

“Yes. I think these projects were a great idea. They really gave me a taste of what I’ve wanted to do in bioengineering and aided in our understanding of what was being taught in class. If you didn’t know what was going on, your project showed it.”

“I think the projects were a very good idea. The projects were definitely a challenge but it was well worth it. Not only did it give us a greater understanding of the concepts but it also challenged us to work together with a group—something that is very impressive.”

“Yes—I feel that the projects allowed us to apply physiology to engineering. We were able to see what it would be like to work on a design while at the same time improving our comprehension of the material.”

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“Yes. I think these projects were a great idea. They really gave me a taste of what I’ve wanted to do in bioengineering and aided in our understanding of what was being taught in class. If you didn’t know what was going on, your project showed it.”

Miscellaneous Comment From a Student Evaluation

“The work on design projects were particularly useful to give us much needed group experience. I had several interviews for co-op positions and their main concerns were with any project experience and questions of experience working with other people for a particular goal. Having these projects gave me some experience that I needed to have successful interviews.”
We thank Dr. Larry Roberts, Tennessee Tech University, and Dr. Jamie Amend, Texas A&M University, for assistance.

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