A Modular Approach to Teaching the Engineering Challenges of Physiology

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SESSION TOPIC: ***Chemical Engineering Education***

We report on a modular approach that has been developed for teaching a course on the engineering challenges of physiology to students having varied background majors and levels of experience. Such a course presents challenges not only in structure, choice of content, and method of delivery, but also in its ability to stimulate and engage students in a highly interdisciplinary subject that can often have a strong medical focus. Our approach includes the delivery of topical materials in short two-week modules by a course director and expert guest lecturers. It also makes extensive use of visual aids, analysis of experimental data sets, weekly topical discussion sessions, and a final group project, all of which serve to integrate key course concepts and provide an invaluable student learning experience

I. INTRODUCTION

Students pursuing studies in the biomedical and electrical engineering fields are expected to have a basic understanding of human physiology, including the underlying physical and engineering principles that drive physiological processes. In a four-credit course entitled "*Engineering Challenges in Physiology*," delivered as part of an accredited biomedical engineering curriculum, students are introduced to key physiological systems, required to solve a variety of engineering problems, and work towards identifying engineering challenges i.e. the needs and opportunities for new techniques, devices, and systems at the molecular, cellular, organ, and whole body scales. Such a course presents "challenges" on multiple fronts. First, the course must be delivered to a mixed student body comprised of double-major undergraduates, M.S. and Ph.D. graduate students, and certificate program students, all with diverse educational backgrounds and varied levels of experience. Course materials must therefore be carefully chosen to engage and challenge, rather than overwhelm and alienate, the students. Second, the course must adequately address the engineering challenges themselves that exist in physiology, and provide students an opportunity to research and propose possible solutions on their own.

In this paper, we report on a modular approach that has been successfully adopted to teach the engineering challenges of physiology. A combination of short and focused lectures, topical discussion sessions, and a final project are all used. The course begins with a review of engineering and physical concepts that underlie all physiological systems, such as those of energy, transport, and information. Specific physiological systems, including cardiovascular, respiratory, renal, and neural systems, are then covered in two-to-four week modules by course and guest lecturers, each an expert and practitioner within his or her own discipline. Each module requires students not only to solve engineering problems, but also interpret real clinical and experimental data, thereby providing an invaluable experiential learning component.

Lectures are accompanied by weekly discussion sessions on current topics reported in the technical and trade literature. The course culminates in final group project presentations that address significant challenges in a particular field such as cardiovascular, space, neonatal, or exercise physiology. The modular approach not only provides short, intensive sessions on key systems, but also gives students an opportunity to integrate personal topics of interest into the course.

II. MODULAR APPROACH TO COURSE DEVELOPMENT AND DELIVERY

II.1 Student and Course Background

The four-credit course entitled "*Engineering Challenges in Physiology*" is one of many courses offered to undergraduate and graduate students as part of the curriculum of the Biomedical Engineering Department at Tufts University in Medford, MA. Rapid growth, both in the field and the department, has produced a number of new program offerings, including the BSBME degree, second major, and minor courses of study at the undergraduate level; ME, MS, and Ph.D. degrees at the graduate level; and a certificate degree in bioengineering, also at the graduate level. Because biomedical engineering is such a highly interdisciplinary subject that crosses the boundaries of science and engineering, it naturally draws students that have diverse educational backgrounds and varying degrees of industrial and professional training. Backgrounds typically range from engineering (electrical, mechanical, chemical and biological) and physics to the life sciences, including biology and pre-medicine. Students having law degrees, or interests in patent law for biomedicine and biotechnology, are also not uncommon. Nearly all students seek to leverage their existing or prior experiences with new coursework and training that will facilitate their future involvement in such areas as biomaterials, tissue engineering, instrumentation, biomedical optics, or neuroprosthetics, to name a few.

In addition to the diverse student body that the course attracts, the subject of physiology and its engineering challenges are, themselves, vast and extensive in scope. While courses in human and medical physiology are mainstays in medical and veterinary curricula, they are also essential for biomedical engineering since they provide a basis for understanding the systems and processes that govern physiological systems, as well as the uses of engineering and technology for monitoring, diagnosis, and treatment of these systems and their dysfunction. A primary challenge in the development and delivery of a course that emphasizes both basic physiology as well as engineering concepts and challenges is, therefore, to define the primary course objectives and the expected course outcomes. The goals and objectives of the course are threefold:

- Provide students with sufficient literacy and fluency in basic physiological processes and systems so that the medical and biomedical uses of engineering and technology can be understood and ultimately applied
- Enable students, through an understanding of universal concepts and themes, to identify engineering challenges, such as the needs and opportunities for new techniques, devices, and systems, at the molecular, cellular, organ, and whole body scales
- Provide an opportunity for application of course concepts through self-study and exploration

Critical to fulfilling the above goals and objectives is deciding on what to present, how to present it, and how to assess progress during the course of the semester.

II.2 Course Structure, Development, and Delivery

To meet the specific needs of the biomedical engineering student, "*Engineering Challenges in Physiology"* was structured and developed to emphasize unifying concepts and themes common to all physiological systems, and delivered using a modular approach that presents material in intensive two-to-four week sessions. Since it is impossible to present all of physiology in its entirety within a one semester course, only a few key physiological systems are chosen for presentation and discussion, including the cellular, nervous, respiratory, cardiovascular, and renal systems. Special topics such as temperature regulation, exercise physiology, high altitude physiology, and hyperbaric medicine are addressed during special sessions at the end of the semester. A summary of the key topics covered in the course are shown in Table I. below.

TABLE I. Outline of topics covered in the course "*Engineering Challenges in Physiology."*

- **Introduction to Engineering in Physiology**
  Human body as a complex system; sensing, feedback, and control
  Physiological parameters, transport, fluid/gas mechanics, chemistry, electrical processes
- **Cellular Physiology**
  Cell structure, cell transport, ion channels
  Potentials (membrane, action), intracellular signaling, neurotransmission
- **Neurophysiology**
  Central and peripheral nervous systems, autonomic and sympathetic processes
  Receptors, neural pathways, sensory (auditory, visual) systems
  Interfacing with the nervous system, neuro-prosthetics, bionic devices
- **Respiratory Physiology**
  Functional anatomy and control of breathing
  Mechanics of breathing, gas exchange (diffusion), ventilation/perfusion matching
- **Cardiovascular Physiology**
  Basic hemodynamics, electrophysiology, electrocardiography
  Mechanical events of the cardiac cycle, peripheral circulation regulation
  Cardiac muscle mechanics, molecular cardiology
- **Renal Physiology**
  Quantitation of renal transport processes, renal tubular function
  Acid/base balance, blood pressure and volume control
- **Special Topics**
  Temperature regulation. exercise, high-altitude, and hyperbaric physiologies
- **Final Projects**
  Student chosen projects in select areas of physiology

Beginning with an overview of the human body, the course proceeds to systematically examine specific physiological subsystems while emphasizing, at the same time, basic engineering concepts and processes that are common to all. These include the notions of energy, information (e.g. sensing, transduction, processing), communications, feedback and control, transport, and use of engineering models (e.g. electrical, mechanical, thermal) to understand behavior at the molecular, cellular, tissue, organ, or whole body scales. Each module explores a new topic or theme related to physiology, and makes use of lecture notes, handouts, text readings [1], supplemental materials [2-8] and homework, such as multiple choice questions and long answer engineering problems, to reinforce key concepts. Each module concludes with a take-home exam that further tests student understanding. A portion of one session every week is devoted to the review and discussion of current events in the science and technical literature, including the use of online journals and science news websites such as *Physiology Online*, *Annual Review of Physiology*, and BrightSurf [9]. This was found to be an extremely valuable tool for removing barriers and engaging students, regardless of prior background or training.

A course director and guest lecturers, drawn primarily from the Tufts University faculty, are each responsible for delivering a topic within his or her own area of specialty. Contributing faculty and lecturers come from the departments of Biomedical Engineering and Biomedical Sciences, School of Veterinary Medicine and the Lung Function Testing Lab, School of Medicine, Molecular Cardiology Institute of the New England Medical Center, and Inner Sea Tech, a small NIH-funded company working in the area of neuroprosthetics. This group was able to provide an extraordinary and unique perspective from the academic, research, clinical, and engineering points of view. Each lecturer developed his or her own lecture materials and handouts, in consultation with the course director.

The course concludes with a final project that gives students an opportunity to explore how the human body and, in particular, its physiological systems, cope with unusual, non-homeostatic conditions, and the impact that such conditions have on overall human health in the short- and long-terms. Here, students in groups of two to three are expected to identify a topic of significance, examine it from as many different engineering and physiological perspectives as possible and, at the same time, integrate key course concepts into their discussion to identify and address specific engineering challenges, along with proposing possible solutions.

III. EXAMPLES OF THEMES AND PROJECTS

Besides the use of a modular approach that provides a suitable framework within which to work, the course benefits from three other key elements. These include the: (1) development and continued emphasis of unifying concepts and themes common to all physiological systems, (2) a demonstrated understanding of concepts, by students, through interpretation of graphical and numerical data of the type derived from clinical and experimental measurements; and (3) identification and analysis of specific engineering challenges across all areas of physiology.

III.1 Development of Unifying Concepts

There are many concepts and themes that can be developed and emphasized in a course of the type considered herein. Two examples of themes that are encountered repeatedly from one physiological system to the next are transport and feedback.

Consider, for example, the process of transport. Students with a background in electrical engineering may be well-versed in drift and diffusion associated with free-charge carriers, but they may be less-familiar with ion or solute transport as it relates to transport across boundaries like cell membranes. Mechanical engineering students might have knowledge of fluid, gas, and heat transport, but be unfamiliar with its role in blood circulation or human respiration. Similarly, students having life science backgrounds may know about ions and solutes, but not have seen the relationship to charge transport in electrical signaling or sensing systems. Hence, one of the themes that is developed within the course is that of transport, where gradients in concentration, potential, or electrochemical potential serve to distinguish between passive and active processes. Once the basic concept has been established, it can be used to discuss the operation of, for example, sodium-potassium (Na^{+}-K^{+}) pumps, osmosis, alveolar gas exchange, or renal tubular filtration. By introducing transport as a process that affects free charge, ions, solutes, fluids and gases, a common theme is therefore established throughout the course that addresses key processes that take place within the respiratory, renal, or cardiovascular systems.

Another example is that of feedback and control, which are key to all engineered systems, are encountered in numerous forms throughout physiology, and can be identified and understood once the basic concepts of a plant, controller, and feedback element are presented and graphically displayed. This method is used extensively to illustrate, for example, the role of positive and negative feedback and control in the muscle stretch reflex, pupillary light reflex, glucose and insulin regulation, the closed-loop Hodgkin-Huxley model, temperature regulation, neuromuscular systems operation, control of arterial blood pressure, autonomic control of the cardiovascular system, and acid/base balance by the renal and respiratory systems. An example of a basic closed-loop feedback system, and a version that is encountered in the Hodgkin-Huxley model that incorporates both positive and negative feedback, is shown in Fig. 1 below.

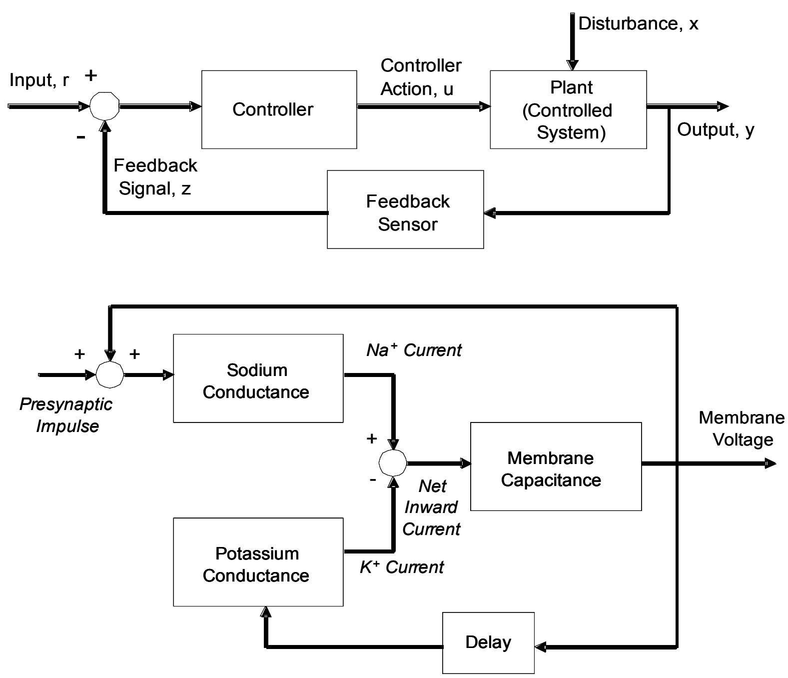

Fig. 1. Illustrations of a generic feedback control system (upper), and that of the Hodgkin-Huxley model (lower) that incorporates both positive and negative feedback.

Other themes that are developed throughout the course include communications, signaling (e.g. electrical, neural, chemical), information processing, and energy (e.g. generation, utilization).

III.2 Analysis of Engineering and Clinical Data

One aspect of the course that provides an invaluable learning experience for students is the solution of engineering problems and the interpretation of real clinical and experimental data. This requires students not only to identify relevant engineering concepts, but also apply them to the solution of specific problems. Here, extensive use of graphs and other visual aids are used to test the understanding of these concepts.

In the module on respiratory physiology, for example, the concepts of flow and pressure-flow relationships are key to understanding the mechanics of breathing. Hence, in addition to learning about the devices and instruments that are used to make physical measurements, such as spirometers and pneumotachographs, it is also important to understand how to interpret key static and dynamic parameters (e.g. pressure, flow, volume, resistance, dynamic compliance). An example of this is shown in Fig. 2

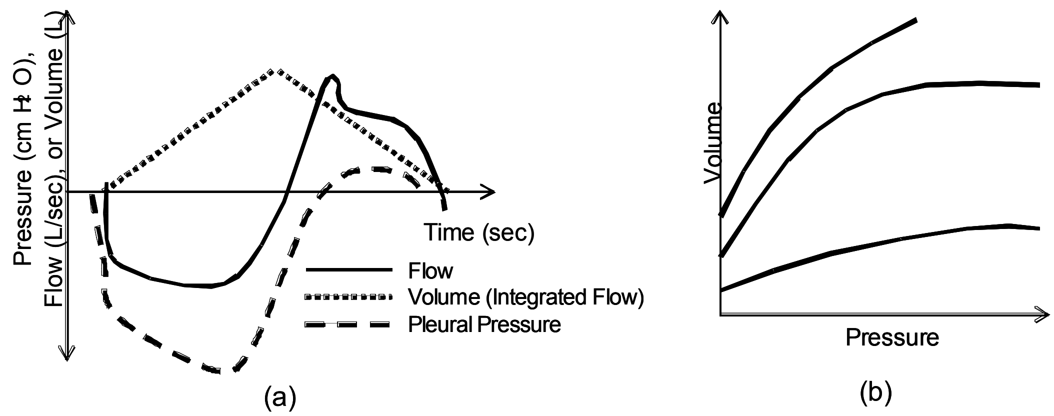

Fig. 2. Graphical data used to illustrate (a) the mechanics of breathing and (b) pressure-volume curves for different patients.

In Fig.2 (a), for example, traces obtained from a single breath by a normal person are given, recorded using a pneumotachograph for flow, integrated flow, and pleural pressure using an esophageal balloon catheter. Using these traces, one must show how resistance (cm H_2O/l/sec) can be computed using the isovolume method. In a similar exercise, several different pressure-volume curves are presented, as in Fig.2 (b), and one must determine the medical condition afflicting the patient (e.g. asthma, emphysema, near-drowning).

A similar approach is used in renal physiology to illustrate the role that the kidneys and lungs play in the process of acid/base balance. This concept can be presented in several different ways, using, for example, the Henderson-Hasselbalch equation, given by pH = pK + log $[HCO_3^-]/0.03\ PCO_2$, or a much simplified expression that defines pH as pH = kidneys/lungs! Alternatively, a Davenport diagram (Fig. 3) that provides a map of the relationships between arterial blood PCO_2, $[HCO_3^-]$, and pH can be used to illustrate various acid/base disorders, including metabolic and respiratory acidosis and alkalosis.

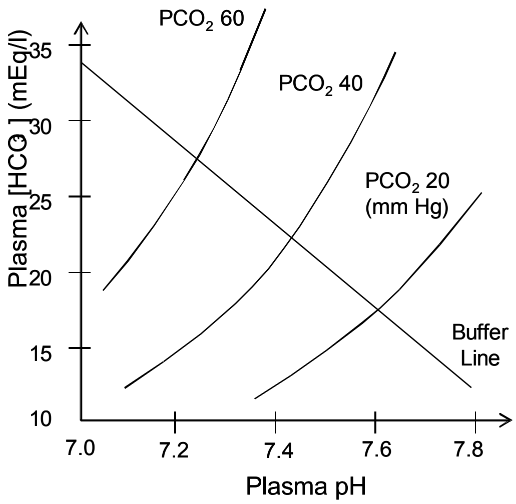

Fig. 3. An acid/base map is used to illustrate the relationships that derive from the Henderson-Hasselbalch equation. The diagram is an effective means of showing how the kidneys and lungs can be used to compensate for acid/base disorders.

To further develop the theme of engineering challenges, many of the modules use take-home assignments that pose open-ended questions or problems to which there are no current solutions. This approach is used extensively in the respiratory physiology module, for example, where students are asked to consider models for instruments or measurement principles that a practicing biomedical engineer might be required to develop. Examples of such challenges include the measurement of frequency-dependent behavior of lung mechanics during human mechanical ventilation, continuous measurement of airway obstruction during sleep, design of an implantable gas exchanger (artificial lung) as an alternative to lung transplantation, or design of asthma-friendly scuba equipment. Each of these require the application of basic concepts and sound physiological principles to the development of new measurement schemes or device designs that could find immediate uses in the marketplace.

III.3 Final Student Projects

A final project in the course provides students an opportunity to further explore, outside of class, the engineering and medical challenges of physiological systems by researching and analyzing the problems associated with a particular physiological condition, and presenting results to the rest of the class in written and oral format. Students are expected to show how they can integrate and apply classroom, book, or lab knowledge of physiology and engineering to a detailed understanding of a specific medical or physiological condition, and determine its impact on other physiological systems of the human body through a discussion of various engineering and medical factors. Some examples of suggested topics proposed for study and those chosen by students are shown in Table II.

The space physiology project, for example, explored the physical response to weightlessness from the first few hours of exposure through an adaptation period. The responses considered included the onset of hypervolemia resulting from bodily fluid shifts, renal diuresis, and cardiac adaptation that ultimately results in decreased cardiac output (CO) and lowered blood volume. It not only discussed the devices used to measure physiological parameters during spaceflight, but also considered methods of dealing with affected renal function, orthostatic intolerance, and the possibility of using artificial gravity as a way to counter the physiological effects of weightlessness.

TABLE II. Suggested topics and examples of final projects chosen by students.

SUGGESTED TOPIC	STUDENT PROJECTS
Space Physiology	*"Physiological effects of fluid shifts on the cardiovascular system during space travel"*
Neonatal Physiology	*"Neurology and the human auditory system"* *"Effects of neutropenia in the neonate"* *"Respiratory physiology of preterm births"*
Sports Medicine Physiology	*"Turning Michael Johnson into a marathon runner"* *"Performance monitoring in cyclists: VO_2 max, lactate threshold, nutrition, muscle function, and power training"*
High-Altitude Physiology	*"Engineering challenges in high-altitude physiology"*
Hyperbaric Medicine	*"Physiology under hyperbaric conditions"*

In a neonatal physiology project, students examined the challenges associated with preterm births, including the development of respiratory distress syndrome (RDS), the problem of impaired surfactant production, and the challenge of monitoring and replacing surfactant levels, as well as the use of drug therapies with corticosteroids to prevent preterm births.

For several students who were interested in sports medicine and physiology, a project related to the performance monitoring of cyclists proved the ideal forum to explore the factors affecting VO_2 max, lactate threshold, performance of different skeletal muscle types, and training regimens that can optimize performance. Typical of most presentations, this work provided a strong physiological background to define the challenges, used graphical data and charts to illustrate key points, and drew analogs to other commonly known facts. An example of these is shown in Fig. 4, where student presentation slides addressed lactate threshold measurement, and the difference between type I, IIa, and IIb muscle fibers as it relates to the common edible chicken!

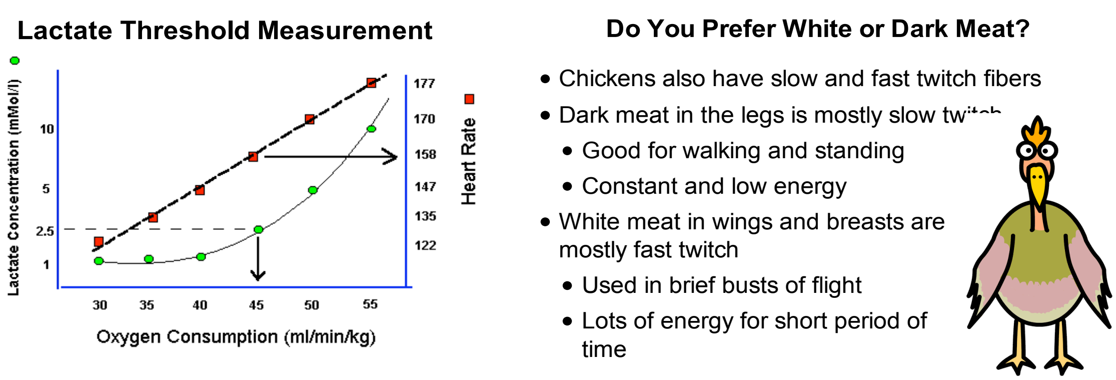

Fig. 4. Example of students slides used to illustrate some of the factors that affect the performance of cyclists, including lactate threshold (left) and muscle type (right).

And, for students interested in scuba diving, the study of physiology under hyperbaric conditions provided an opportunity to further investigate such concepts as Dalton's Law, tissue saturation, nitrogen narcosis, and the neurological effects of gas partial pressure, including lipid bilayer alteration and modification of neuronal firing rates.

IV. CONCLUSIONS

The modular approach described herein to the study of engineering and its challenges in the many areas of physiology has, to date, proven successful. Due to its breadth, interdisciplinary nature, and use of faculty and lecturers who bring their knowledge, practical expertise, and clinical and experimental training to the course, "*Engineering Challenges in Physiology*" has proven to be an intensive, challenging, and rewarding experience for many biomedical engineering students. While the course focuses on concepts and themes that are common to different physiological systems, it also attempts to relate processes and behavior from the molecular and cellular levels to those at the organ and whole body scales. Through an understanding and working knowledge of basic processes and physiological parameters, it is expected that biomedical engineering students who have taken a course like that described herein will be better prepared to identify new engineering challenges, propose unique solutions, and develop new technologies that address specific needs in the biomedical and biotechnology fields.

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9. See, for example, *Physiology Online* (physiologyonline.physiology.org), *Annual Review of Physiology* (physiol.annualreviews.org), and BrightSurf (www.brightsurf.com).

BIOGRAPHY

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