Using Modeling and Simulation to Teach Dynamic Systems Concepts in the Context of Physiology

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Bioengineering is a discipline that requires a thorough understanding of both dynamic and physiological systems. Many curricula force an artificial separation of these topics by teaching system dynamics in an engineering school department (such as mechanical engineering) and physiology in a medical school department (such as basic science). At the University of Pittsburgh and Washington State University, we combine them in a single course.

Products Used

- MATLAB®
- Simulink®

At the University of Pittsburgh, BIOENG 1255–Dynamic Systems: A Physiological Perspective teaches the principles of dynamic systems in the context of physiology. In lab sessions, students apply the system dynamics concepts that they've absorbed in lecture by using MATLAB® and Simulink® to model and simulate physiological systems. They use the models to solve problems drawn from real-world biological applications, including diabetes diagnosis, blood-alcohol-level analysis, and arterial circulation and blood pressure studies. For the first time, students begin to view the body and its organs quantitatively, as dynamic systems.

Lectures and Labs

The 14-week course, a requirement for all University of Pittsburgh bioengineering juniors, comprises two 75-minute lectures and one three-hour lab session each week. Lectures cover traditional dynamic systems and modeling concepts, including the use of balancing techniques and constitutive laws in model development, system characterization (dynamic order, linear/non-linear, time-invariant/time-varying, and autonomous/non-autonomous), linearization techniques, and time- and frequency-domain analyses. In addition, we place a great deal of emphasis on generalized thinking and analogous representations.

Each lab workstation is equipped with MATLAB and Simulink. The University of Pittsburgh acquired a Total Academic Headcount license for MathWorks products, which means that they can be installed on any university-owned computer. This makes it easy for students to access MathWorks tools in their first year, when they are required to learn MATLAB, and throughout their studies. Students can complete lab work on their own laptops, but we encourage them to work in the lab, where we can answer questions and provide other assistance.

We currently restrict the course to bioengineering students to keep class sizes manageable. We could accommodate more students in the lecture portion, but 60 is the most that we can have in the lab sessions and still provide one-on-one instruction.

Dynamic Systems with a Twist

A distinguishing feature of our dynamic systems course is the emphasis placed on generalized thinking and analogous representations. Bioengineering students benefit from understanding the similarities between organ systems and the physical-biological concepts that underlie them. In many physiology courses, different organ systems are taught independently. For example, students study the cardiovascular system for a few weeks and then move on to the respiratory system, with scant attention paid to the fact that the physical principles that govern blood flow—pressure, resistance, compliance, and so on—also govern air flow.

We extend the idea of generalized thinking and analogous representations beyond physiology by bringing in problems from seemingly disparate domains, including mechanical, hydraulic, thermal, and chemical.

Once students understand the principles that apply in all these domains, they can confidently tackle all sorts of problems because they see the patterns that they share. The students discover that, when you break the problems down to their most basic level, they can all be described using the same conceptual and mathematical tools.

MATLAB and Simulink are ideal for learning dynamic systems with this emphasis on generalized thinking. MathWorks tools are used by professional engineers in a wide range of disciplines, and they enable students to model and simulate dynamic systems using the basic concepts that underpin them all.

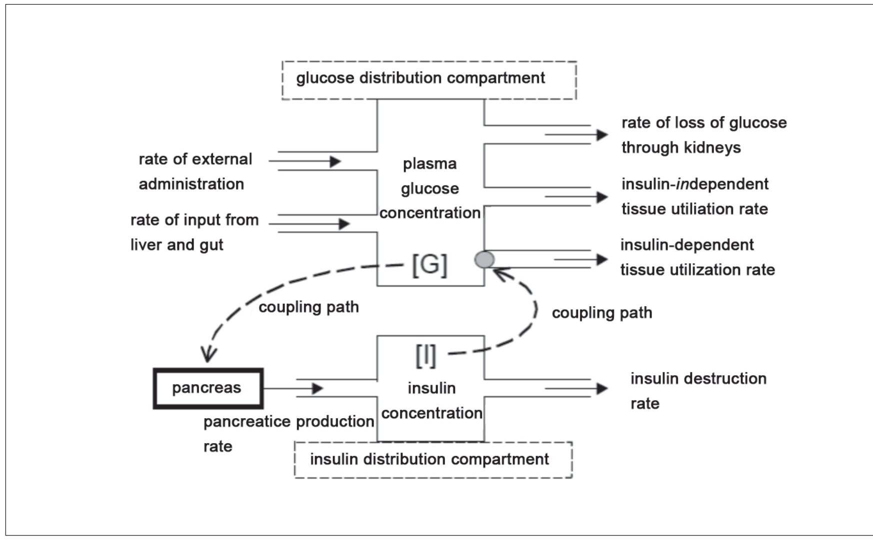

Figure 1. *Diagram of the relationship between glucose and insulin in the human body, provided in the background material for the glucose-insulin lab.*

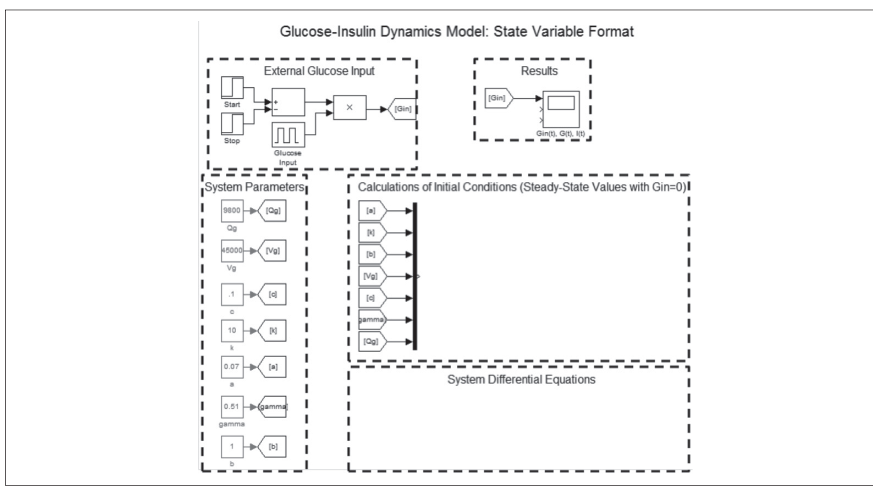

Figure 2. *The starting model for the glucose-insulin lab.*

Glucose-Insulin Dynamics and Diabetes

The lab modules cover diverse physiological topics, including systemic arterial circulation, fluid homeostasis, neuronal integrative function, blood alcohol dynamics, glucose-insulin dynamics and diabetes, and pulmonary gas exchange. While the physiological and system dynamics concepts explored differ from lab to lab, all labs share a common structure: Students are presented with a biological or physiological question and background information on the lab's main topic. They develop a mathematical model of the (simplified) underlying system using differential equations and then build a Simulink model to solve these equations. Finally, they run simulations in Simulink and perform sensitivity analysis to find quantitative answers to the lab's central biological questions.

In the lab on glucose-insulin dynamics and diabetes, for example, students explore ways to distinguish type I diabetes, in which insulin production is diminished, from type 2 diabetes, in which the functional effects of insulin for a given concentration are reduced.

We give students a schematic diagram of the system to be modeled (Figure 1) and some background information. Students derive the system differential equations that predict the plasma glucose concentration and plasma insulin concentration given a set of system parameters and inputs (the rate of insulin production and the rate of external glucose administration).

Students then use Simulink to build a model comprising integrators and other basic arithmetic blocks for solving differential equations. To get the students started, we provide them with a basic model that includes nominal values for system parameters (Figure 2). They then simulate a glucose tolerance test using their Simulink models.

In the real world, a physician typically conducts this test by introducing glucose into a patient's blood after a period of fasting and then measuring the change in blood glucose over time. In Simulink, the students can monitor this change in their models just as a physician would in a real patient.

In the next phase of the lab, students perturb various system parameters one at a time and then rerun the simulation. We ask them to observe the effects of decreased insulin production (as occurs in type 1 diabetes) and decreased insulin-dependent glucose metabolism (as occurs in type 2 diabetes). The students run simulations for normal, type 1 diabetes, and type 2 diabetes conditions and plot glucose and insulin concentrations as they change. Based on these observations, they have to explain how a doctor might diagnose diabetes—and the specific type—by examining real-world blood samples during a glucose tolerance test.

A Quantitative Approach to Biology

Biology is becoming more quantitative, with mathematical modeling replacing descriptive characterization and trial-and-error approaches to biological system analysis and control. When you deal with qualitative collections of facts and rely on your mind to formulate the overall model, you often miss important details. A quantitative framework enables us to develop a better understanding of complex systems and the various feedback loops within them.

It might be argued that quantitative models are only rough approximations of the real systems they represent. While it is true that no model can perfectly reflect a complex physiological system, the models can and do help engineers and engineering students understand complex systems. More importantly, engineers design systems that will interact with native physiological systems. In this regard, quantitative models are a necessity for the design process. It is generally more efficient to engineer a device that can correct a faulty physiological system—or to make such a system behave in a certain way—by first modeling and simulating the device and the system together. Simulink is a user-friendly and versatile environment for such in-silico design and experimentation.

We plan to develop a follow-up, laboratory-based course that focuses on biological control. For example, students might use Simulink to design and simulate a closed-loop control system that monitors blood pressure and delivers appropriate levels of an anti-hypertensive drug. Bioengineers are already designing closed-loop control systems like this today. In fact, one of our former students told us that he is using much of what he learned about modeling in BIOENG 1255 to develop controllers for a left-ventricle assist device that his company is developing. ■

About the Authors

Dr. Sanjeev Shroff is Associate Chair, Department of Bioengineering, and Professor and Gerald McGinnis Chair in Bioengineering at the University of Pittsburgh. His research interests include contractile and regulatory proteins and whole heart function, vascular stiffness and cardiovascular function, and large-scale mathematical simulations of biological systems for research, education, and engineering design.

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