AC 2011-2403: DEVELOPMENT AND DELIVERY OF A PHYSIOLOGICAL TRANSPORT PHENOMENA COURSE

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Introduction:

From a chemical engineer's viewpoint, functioning of the human body can be seen as a complex biological industrial plant composed of a network of interrelated unit operations with the capability to respond to environmental changes. The mention of unit operations immediately triggers the thought of underlying transport processes. True to this thought, several aspects of human body function, particularly those relating to physiology can be treated as transport phenomena problems. In fact in the last fifty years chemical engineers have contributed significantly to various innovations in physiology such as characterization of vascular fluid transport, kidney dialysis machines, drug delivery vehicles, and artificial tissue constructs to name a few.

Major reasons for applying transport phenomena principles to physiological systems are: (i) To better understand the physiological functions of the human body, (ii) to diagnose pathological conditions which are typically reflected by changes in transport processes, and (iii) to develop instrumentation and intervention technologies for therapies. Due to its great potential in solving biomedical problems an increasing number of chemical engineers are using transport phenomena principles in biomedical process development and in biomedical research. Hence, a course in physiological transport phenomena is necessary and appropriate.

This paper will discuss some experiences in developing an integrated physiological transport phenomena course that is targeted to students at the junior to graduate level. Transport phenomena and physiology were taught concomitantly thus instantly establishing the connection between these two disciples. Course content included a wide a variety of topics ranging from cellular transport processes to transport in organs and tissues to transport under pathological conditions to transport in biomedical devices. Instructional materials for this course included parts of multiple textbooks, several journal articles and web resources. Students were actively engaged in peer instruction through weekly journal club discussions.

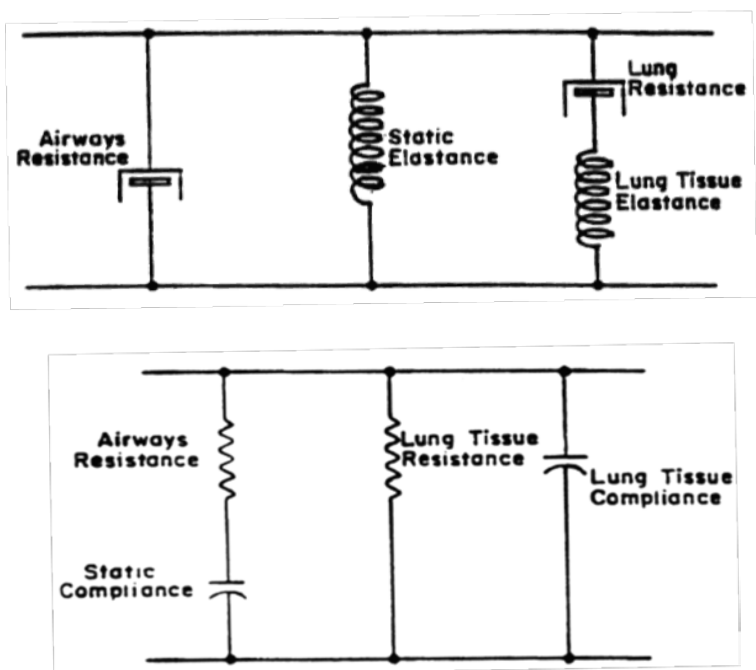
Early history of teaching physiological transport phenomena:

Teaching physiological transport phenomena is hardly a novel idea. Several courses of this essence are offered in many engineering programs. As early as 1964 the University of Michigan offered a summer course on Physiology for Engineers where several physiological concepts were explained through engineering principles. Though the course had a physiology focus, its attendee statistics given in Table 1 provide some important information about the background of engineers working in physiology area at that point of time: (i) Amongst engineering disciplines, mechanical and electrical engineering were dominant in the field of physiology with chemical engineering forming only a significant minority, (ii) chemical engineering had the highest level of involvement at the doctorate level implying that this discipline might be contributing most to advancements in physiology research compared to other engineering disciplines.

Table 1: Number of participants in a summer course on Physiology for Engineers during the year 1964.

Discipline	Bachelors level	Masters level	Doctorate level	Total
Aeronautical	2	1	0	3
Chemical	3	0	3	6
Electrical	16	3	1	20
Mechanical	10	3		13
Other	1	4	0	5

The first observation indicated that electrical and mechanical engineering disciplines influenced the engineering analysis of physiology in the early stages. This was reflected in a few transport phenomena textbooks which were written with an electrical or mechanical engineering slant and also the early inception of bioengineering divisions/sections in electrical and mechanical engineering professional organizations and journals. Consequently, instruction in physiological transport phenomena heavily relied on analogies from concepts like resistance and compliance (electrical engineering concepts) or resistance and elastance (mechanical engineering concepts). An example of such analogy for pulmonary function is given in Figure 1.



(a)

(b)

Fig. 1: Representation of pulmonary function. (a) mechanical engineering analog, and (b) its electrical engineering equivalent.

The advantage of using analogs is the immediate availability of well-studied functional equivalents. Thus known concepts, theories and equations were readily applied to understanding and solving problems in physiology. However, this approach treats the physiological process at a macro or a global level and takes a ‘black box’ approach which provides only a limited insight into the science of the process. Nevertheless, this approach added a huge amount of knowledge in the field of transport processes in physiological systems. The electrical and mechanical engineering approach to transport phenomena continued well into 1990s and is still being practiced in many courses.

The advent of chemical engineering approach to physiological systems:

As more chemical engineers explored physiology, chemical engineering principles diffused into this field. Observations from the data given in Table 1 indicated that even in the early stages chemical engineers were significantly involved in physiology at the research level, but contributed less at the education level. This trend started to change in the 1990s and the 2000s during which time chemical engineering programs started offering biological transport phenomena or similar courses. In many instances, biological examples were included in traditional transport phenomena courses. This is currently an ongoing effort and more needs to be done to enhance learning of physiological transport processes. Developing a comprehensive physiological transport phenomenon textbook with a chemical engineering perspective and developing instructional materials to deliver the necessary physiology background information are appropriate efforts on that direction.

The maturity of chemical engineering applications in physiology created a unit operations approach to study living systems. Therefore, instruction of physiological transport phenomena will naturally take this approach. Figure 2 depicts a unit operations approach for pulmonary function in living systems, a process identical to the one described in Figure 1. It is evident that an unit operations approach allows for more than one presentation of the system depending on the aspect that is being focused. It could be a simple ‘black box’ approach (Fig. 2a) or a deeper mechanistic approach (Fig. 2b). Thus, chemical engineering analysis allows the process (in this case gas transport in the lung) to be disassembled into various sub-processes which can then be analyzed using known transport phenomena principles (appropriate equations and boundary conditions are developed and solved) followed by reassembling the process to make inferences about the whole system (in this case the lung). The unit operations approach formed the basis for developing and delivering the course under discussion.

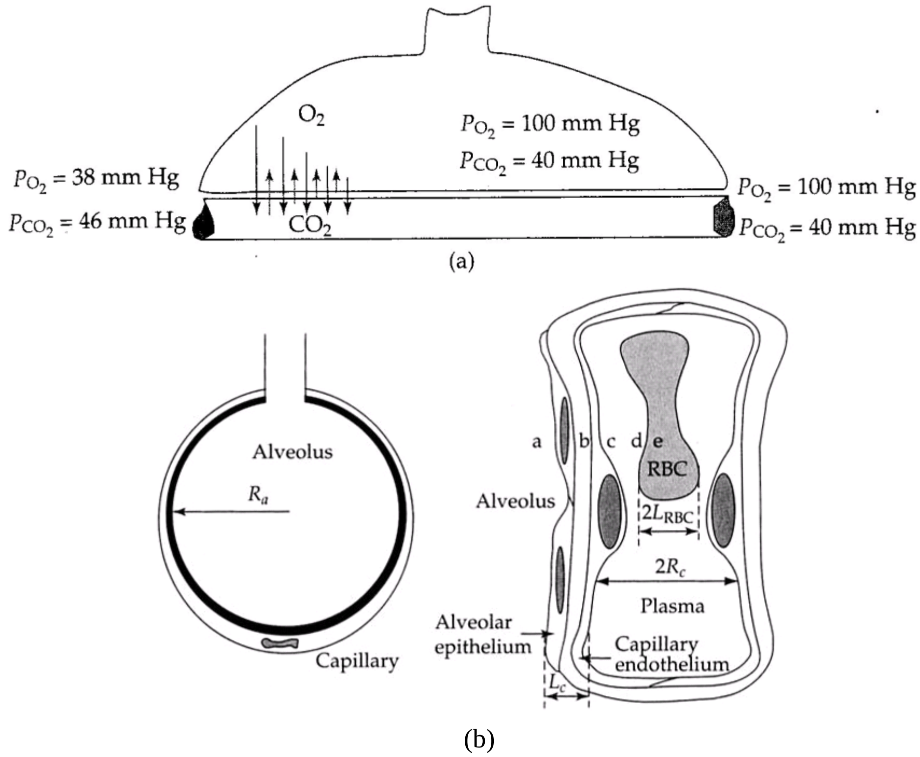


Fig. 2: Representation of pulmonary function through unit operations approach. (a) black-box method, and (b) a mechanistic method depicting gas transport in the lung.

A unified instruction method to address cross-disciplinary challenges:

A general challenge in a teaching a cross disciplinary course is the ability to actively engage students in the learning process and to foster an environment of heightened curiosity and inquiry. A challenge particular to this course is to provide an immediate relationship between the two seemingly varied subjects of physiology and transport phenomena. It is also important for the students to connect with the topics being discussed. Course content, structure and delivery were carefully chosen to address the above challenges.

Available textbooks on biological transport phenomena use a modular approach of instruction, i.e., physiology and transport processes are taught in modules which are combined during later part of the course to complete the cross-disciplinary learning. This approach would have students spend more than half of the course without realizing the connection between physiology and transport phenomena. The present course was however designed for concomitant learning of these two disciplines. One physiological process (such as transvascular transport, gas transport, transport in kidneys, etc.) was typically discussed per week. One-third of instruction time was devoted to each of the following in that particular order: discussions on physiology of the process, discussions on relevant transport principles underlying the physiological process and, a student-chaperoned journal club discussion of a research paper (mostly with clinical or animal model data) that connected the physiological processes to the transport principles. This approach improved instruction in two ways: (i) It provided an immediate relevance and application to the topics being discussed – students clearly understood why they were learning a particular topic and the interface between physiology and transport phenomena, and (ii) it actively engaged students during journal club discussions – students had a chance to apply the new knowledge they had acquired in any particular week to analyze and critique research data – this gave them a sense of achievement and encouraged further learning. By chaperoning the journal club discussions, students were able to gain a sense of belonging and ownership to the materials discussed during class. Journal clubs also offered an opportunity for peer instruction.

To further enhance collective learning, students were required to complete a term paper project which had several parts designed to apply concepts learnt in class to research data. Term paper projects were done in teams of 2-3 students each. Student teams were encouraged to come up with their own projects that included abundant applications of transport phenomena in physiology. Projects were then approved for further study based on a written proposal. The term paper project composed of several parts: (i) Proposal – a brief introduction to the chosen topic, and a persuasive discussion on the urgency and need of the topic supported by data on its benefits to cost, healthcare, quality of life, society, etc. Topics were required to be at the interface of physiology and transport phenomena, (ii) comprehensive survey of literature, (iii) critical analysis of literature information – this was students' original work comparing, critiquing and interpreting literature information, deriving their own conclusions, identifying deficiencies and proposing improvements, and (iii) analysis of ethical concerns and regulatory issues related to the topic.

Term paper projects were evaluated through brief periodic reports and a formal powerpoint-based presentation at the end of the course. Example term paper projects completed by student groups include: Drug inhalation - tennis court-effect in drug delivery, Transport processes in mammalian placenta during embryo development and growth, Tumor metastasis: transport challenges of the tumor cell, Biomechanics of pulmonary edema and its effect on gas exchange, etc. The term papers projects served as a nodal point where physiology, transport phenomena, critical thinking, and communication skills converged. The term paper projects also provided an opportunity for the class and the instructor to enhance and expand their knowledge in physiological transport phenomena.

Course details:

This course typically satisfied an elective requirement or requirements for several certificate programs and was open to undergraduate engineering students with junior standing or above and to graduate students. Prerequisites included at least one transport course and one chemical reaction kinetics/reaction engineering course which can be taken concomitantly. Though it was not a prerequisite, most students had taken at least one sophomore level biology class (typically cell and molecular biology), but usually did not have a background in physiology. This course has been taught twice and the historical student composition in this course is given in Table 3.

Table 3: Percentage student composition in the physiological transport phenomena course

Graduate level	Senior level	Junior level
23 %	72%	5%

It is interesting to note that junior level students hardly take this course though it is open to them, Reasons for this are currently unknown, and efforts will made in the future better understand this trend and subsequently accommodate junior level students.

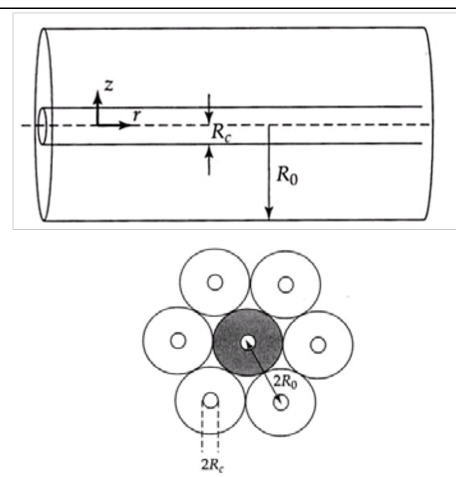
Course syllabus:

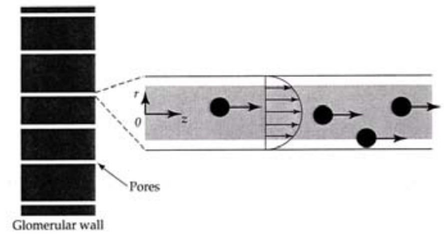
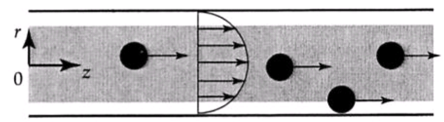
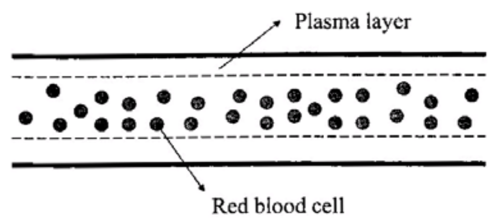
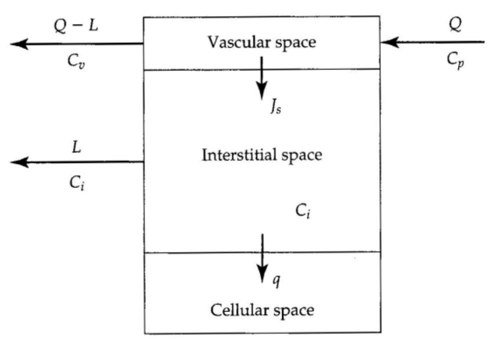
The physiological transport phenomena course covered the following topics: (i) Transvascular transport, (ii) Gas transport in blood and tissues, (iii) Transport in kidneys, (iv) Transport processes in circulation and microcirculation, (v) Ligand-receptor interactions and transport of molecules within cells, (vi) Cell adhesion, (vii) Transport in medical devices, (viii) Transport in tumors and artificial tissues, (ix) Pharmacokinetics and pharmacodynamics.

Physiological transport process examples:

A few physiological examples from this course which can be adapted to traditional transport phenomena courses are listed in Table 4.

Table 4: Some applications of transport phenomena principles to physiological systems.

Physiological process	Underlying transport principles and equations	Schematic
Oxygen delivery to tissues	One dimensional diffusion and reaction through a cylinder: $$\frac{D_{O_2}}{r}\frac{d}{dr}\left(r\frac{dC_{O_2}}{dr}\right) = R_{O_2}.$$	

Solute transport in the glomeruli	Mass and fluid transport through pores $$v_z = 2v_m\left[1 - \left(\frac{r}{R}\right)^2\right]$$ $$N_s = -D_0\frac{dC}{dz} + Cv_z$$	 
Farheus effect in blood flow	Segregated fluid flow in pipes (marginal zone theory) $$\tau_{rz} = \frac{(P_0 - P_L)r}{2L} = -\mu_c \frac{dv_z^c}{dr}$$ $BC1: r = 0, \frac{dv_z^c}{dr} = 0$ $BC2: r = R - \delta, \tau_{rz}\|_c = \tau_{rz}\|_p$ $$\tau_{rz} = \frac{(P_0 - P_L)r}{2L} = -\mu_p \frac{dv_z^p}{dr}$$ $BC3: r = R - \delta, v_z^c = v_z^p$ $BC4: r = R, v_z^p = 0$	
Generalized model for drug transport in an organ	Mass flow balance For vascular space: $$V_v\frac{dC_v}{dt} = QC_p - (Q - L)C_v - J_s + R_v,$$ For interstitial space: $$V_i\frac{dC_i}{dt} = J_s - \frac{LC_i}{Z} - q + R_i$$ For cellular space: $$V_c\frac{dC_c}{dt} = q + R_c,$$ Overall mass transport: $$V_t\frac{dC_t}{dt} = QC_p - (Q - L)C_v - \frac{LC_i}{Z} + R_t$$	

Future plans:

Future plans for this course include: (i) Adding guest lectures by medical school faculty on physiology topics, (ii) annotating currently available physiology education modules with transport phenomena concepts for easy reference to engineers, (iii) inclusion of a virtual or web-based lab module to design, conduct and analyze experimental data, (vi) investigate the lack of patronage from junior level students and take remedial action if necessary, (v) expand the scope of this course to include students from other engineering disciplines (biomedical, electrical and mechanical).