Article

Changes in Chemistry and Biochemistry Education: Creative Responses to Medical College Admissions Test Revisions in the Age of the Genome†

Charles Brenner*

From the Department of Biochemistry, Carver College of Medicine, University of Iowa, Iowa City, Iowa 52242

Abstract

Approximately two million students matriculate into American colleges and universities per year. Almost 20% of these students begin taking a series of courses specified by advisers of health preprofessionals. The single most important influence on health profession advisers and on course selection for this huge population of learners is the Medical College Admissions Test (MCAT), which was last revised in 1991, 10 years before publication of the first draft human genome sequence. In preparation for the 2015 MCAT, there is a broad discussion among stakeholders of how best to revise undergraduate and medical education in the molecular sciences to prepare researchers and doctors to acquire, analyze and use individual genomic and metabolomic data in the coming decades. Getting these changes right is among the most important educational problems of our era. © 2013 by The International Union of Biochemistry and Molecular Biology, 00(00):000–000, 2013

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The 2015 MCAT Revision

In 2008, the Association of American Medical Colleges created a process to revise the Medical College Admissions Test (MCAT) [1]. In this process, which was managed by the MR5 advisory committee, 2,700 college and medical school faculty were interviewed to distill the most valuable concepts taught to baccalaureate students and the core competencies most likely to be missing from the education of medical students. Biochemistry emerged as the discipline most important for mastery of the medical school curricula of the future [2]. In addition, the MR5 committee concluded that some students get into medical school with little exposure to multicultural issues, and with poorly developed analytical skills and ethical awareness, which could be strengthened by studying literature and the humanities. As a result of these reports [3–5], the 2015 MCAT will test biochemistry for the first time, expand testing in psychosocial competencies, and include a critical analysis and reasoning component.

Student enrollment data in recent years effectively foreshadowed the biochemistry requirement. Although biochemistry has not been a required premedical course at most medical schools, biochemistry is such a foundation piece of the medical school curriculum that well-informed premedical students already knew that they should find time to take biochemical coursework in college. To molecular scientists, the more surprising pieces of the MR5 recommendations relate to increased requirements in psychosocial competencies, critical analysis, and reasoning. Indeed, when one reads the recommendations and commentaries about the types of people needed in healing professions, it becomes clear that rigid, science-based premedical curricula may be homogenizing the applicant pool into students who excel in multiple choice exams but have little exposure to art, literature, or the complexity of the human condition [6]. Thus, simply to add new required courses to an already rigid set of required prehealth courses would not be responsive to the identified problems.

Putting the opportunity for curriculum revision positively, one need only survey the current state of biomedicine. There is virtually no barrier to entry of an individual to obtain

*Address for correspondence to: Charles Brenner, Department of Biochemistry, Carver College of Medicine, University of Iowa, Iowa City, Iowa 52242. Tel.: 319-335-7934; E-mail: charles-brenner@uiowa.edu.

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personalized genomic information. The single nucleotide polymorphism panel performed by 23andme now costs only $299. Full genome sequencing and metabolomic panels continue to decline in cost and increase in the sophistication of analysis. Once these analyses are performed on a research subject or patient or are brought to a physician's attention by a patient, biochemical insight is required. Mutations always lead one to question whether macromolecules are altered in expression, stability, and/or function. Altered metabolites and genes always point to pathways that are dysregulated and require one to develop hypotheses to connect these alterations to phenotype. The ability to analyze genomic, transcriptomic, proteomic, and metabolomic data will depend on effective chemical and biochemical training.

Chemistry and STEM Literacy

The first and most obvious points to address with respect to the typical prehealth curriculum is that approximately five semesters of it lives in chemistry departments and that the majority of students do not complete it or complete it with performance insufficient for admission to medical school. These facts impose unique stresses and responsibilities on chemistry departments.

Because chemistry departments have the task of teaching large numbers of new students every year, they are responsible for exposure of a significant proportion of learners to scientific methods and for the establishment of foundational scientific literacy. The 375,000 annual students in general chemistry do not fully know yet what their strengths, weaknesses, and interests are. Some of these students will continue in health preprofessional tracks, whereas other students will pursue scientific research, engineering, computational studies, law, social and behavioral studies, humanities, and arts. Among the scientists, engineers, and premedical students in general chemistry, a few will be chemistry majors, but the majority will pursue majors in other departments that require foundational coursework in chemistry. Nonetheless, chemistry departments typically require majors and nonmajors to start the same way, that is, with two semesters of general chemistry, followed by two semesters of organic chemistry and an organic synthesis laboratory.

Different universities have developed different ways to manage the annual influx of students in the prehealth professions. At the University of Iowa, the Department of Biology requires students to take chemistry before biology. At the University of Texas at Austin, the Department of Chemistry and Biochemistry requires students to take calculus before chemistry. These prerequisites and interdependencies have the effect of making one or more department the early filter for unprepared or poorly disciplined students with prehealth professional interests.

Whereas colleges and universities have actively managed some of interdependencies and sequencing of courses in different departments, this is not always the case. For example, undergraduate biochemistry at the University of Iowa is offered as a one-semester course for nonmajors and as a two-semester course for majors. Although the biochemistry majors' course requires and builds on organic chemistry, the higher enrollment nonmajors' course does not require organic chemistry. Because undergraduate advisers and medical school admission committees will never know as much about what is taught in particular courses as the faculty, it behooves colleagues to reach across departmental silos to develop thoughtful curricular recommendations that build interdisciplinary knowledge. If faculty members from different departments do not take the lead to work together to develop a new premedical curriculum, we may wake up to discover "light" or disconnected courses as new *de facto* requirements.

American Society for Biochemistry and Molecular Biology Recommendations

In the 2012–2013 academic year, premedically oriented freshmen began studies that must prepare them for the 2015 MCAT. The precise content of the test is unknown and the underlying MR5 documents refer to core competencies that should be achieved rather than courses that should be taken [5]. With American Society for Biochemistry and Molecular Biology (ASBMB) membership representing large numbers of faculty in departments of chemistry, biology, biochemistry, and molecular biology, in December of 2011, then ASBMB President Suzanne Pfeffer charged me to develop premedical curriculum recommendations both to respond to MR5 recommendations and to help develop the next generation of biomedical researchers who will take coursework side by side with premedical students.

I spoke to educators at Brandeis, Iowa, Dartmouth, Purdue, Texas, Stanford, San Jose State, Haverford, Macalester, and elsewhere to understand how undergraduate education is managed at different institutions and to study how undergraduate preparation affects graduate and professional performance. Dagmar Ringe and I wrote the recommendations and obtained endorsements from more than a dozen national leaders in chemistry and the life sciences [7]. Although we are certain that there is room for reform and innovation in premedical mathematics, physics, psychosocial, and humanities education, we did not feel qualified to offer recommendations in those areas. Rather, we attempted to develop recommendations that will focus biology, chemistry, and biochemistry course requirements without adding a lot of additional time.

One Year of Biology

The first recommendation stated, "The introductory year of biology should be refreshed (if it has not been already) to prepare students in cellular and molecular biology up to and

including fundamentals of genetics and biological information transfer." This recommendation attracted little controversy—all of the newer introductory biology textbooks possess a strong genetics focus. The traditional strength areas in biology departments, including evolution, environment, zoology, botany, microbiology, and development, have all been revolutionized by work in molecular genetics. Accordingly, the typical introductory biology course for majors and nonmajors alike is ideal for premedical students.

Chemistry for Life-Oriented Students

The second recommendation stated, "The traditional, two-year sequence of general and organic chemistry should be streamlined to a single year of life-oriented chemistry that focuses on bonding and reactivity of molecules containing carbon, oxygen, phosphorus, sulfur and nitrogen." This recommendation attracted the most controversy, in large part because of the stress induced by the word "streamlined" and the lack of specificity about what would be included in a course on "life-oriented chemistry." Dagmar and I were not trying to imitate Alan Greenspan, who once stated, "If I turn out to be particularly clear, you've probably misunderstood what I said." Although clearly stating than a chemistry course should be developed for this cohort, we were trying to avoid being overly prescriptive.

Life-oriented chemistry will clearly spend less time on alkanes, alkenes, and alkynes than does traditional organic chemistry and will focus on functional group reactivity of biomolecules. In addition to defining what should be in this course, there will be at least two substantive issues created by developing it. First, because precollege preparation varies widely, the general chemistry that precedes this course needs to be carefully considered. Second, because life-oriented chemistry will have less organohalide and petrochemistry in it than a traditional organic chemistry course, it will not contain all of the material for students who plan to do synthesis.

Although I am not a member of a chemistry department and I continue to think that chemistry departments should think creatively about how to teach chemistry to life-oriented students, I am happy to provide more specificity about one way in which changes could be implemented. These ideas are my own and not those of ASBMB. However, they provide some practical guidelines that may assist in implementation of an institution's premedical course offerings to be consistent with ASBMB recommendations [7].

Currently, many larger chemistry departments offer separate general and/or organic chemistry courses for majors and nonmajors. The nonmajors' courses are the "light" versions, which require less work for an A. I suggest that the resources going into teaching chemistry for nonmajors be repurposed to develop a new two-semester course that teaches reactivity of biomolecules.

At many schools, life-oriented chemistry can be developed as an alternative to the traditional organic chemistry course. I suggest that the requirement for this course be one semester of general chemistry or a high score on advanced placement chemistry. To optimally coordinate freshman chemistry majors with those in the life science and prehealth tracks, chemistry departments might consider going to a 1:2:1 curriculum [8], such as that which has been implemented at Indiana University. In the second semester, majors would begin traditional organic chemistry, whereas life-oriented students would begin the new course.

In my opinion, the new course need not be a combined organic chemistry–biochemistry course, because a biochemistry course should sit atop a very rigorous year of chemical reactivity. The course ought rapidly to consolidate concepts from general chemistry on bonding, reaction coordinate diagrams, and acid–base chemistry. With time freed up from classical organic synthesis, the course may concentrate heavily on functional groups including amino acid side chains, phosphoric acids, key carbohydrates, lipids, and cofactors. Enzymatic counterparts to classical organic reactions (hydrolysis of esters and amides, aldol condensation, Claisen condensation, and Michael addition) would form the life-oriented heart of this course. Although it will require some time to introduce protein structure, I would intentionally not cover the biochemical topic of macromolecular structure in a comprehensive way in order to focus on chemical reactivity.

Based on conversations with publishers, I do not believe that this course will be lacking textbooks for long, nor do I believe it will dumb down organic chemistry. In fact, I expect that replacing organic chemistry for nonmajors with this course will better prepare a large population of learners to do research or health professional practice in a genomic and metabolomic world. Whether the envisioned alternative organic chemistry course will be seen as a valid substitute course for chemistry majors, I cannot anticipate. Perhaps, some institutions will develop new advanced synthesis courses for chemical biologists and future practitioners of nuclear medicine.

Biochemistry Based on Chemistry

The third recommendation stated, "A one-semester biochemistry course should be required and a two-semester biochemistry course recommended for premedical students. The material must broadly introduce macromolecular structure/function and cellular metabolism." This recommendation has not been particularly controversial. Whether a biochemistry course is taught by members of a chemistry department, a biology department, or a biochemistry department, it is important that the course builds on what is taught in the chemistry of functional groups. For example, we aim for students to understand that class I aldolase performs a reverse and a forward aldol

condensation reaction in the glycolytic and gluconeogenic directions of glucose metabolism.

Distribution of the Research Methods Requirement

The fourth recommendation stated, "A single biology, chemistry or biochemistry laboratory course emphasizing research methods and statistics should be required. The content is expected to vary with the department offering the course. For example, a biology laboratory might utilize fluorescent reporters of gene function. A chemistry laboratory might consist of the traditional organic chemistry material or a bioanalytical unit that focuses on quantifying carbohydrate and lipid metabolites. A biochemistry laboratory might characterize enzymes. Each of these methods courses would be expected to cover statistics and data analysis." This recommendation has been strongly welcomed by faculty in a variety of departments, including some we had not thought of earlier. For example, students in a health and human physiology laboratory could conduct properly consented human performance experiments, accompanied by statistics and data analysis. Medicine is such a broad field that it will benefit students greatly to provide them broad choices in electing research methods. Broader distribution of laboratory instruction should provide a benefit to departments.

Further Prospects

Save for a small number of institutions, 2012–2013 freshmen premeds are likely to be highly scheduled during college, because they will be adding biochemistry and psychosocial coursework to the traditionally required courses, while taking enough time to read literature and become nuanced young adults. A life-oriented organic chemistry course, taught after a semester of general chemistry and in preparation for biochemistry, will allow the academy to prepare young people with greater molecular foundations for medicine and improve their preparedness for genomic and metabolomic research in about the same amount of time allotted to the traditional premedical curriculum. Of course, because students are aiming to achieve competencies, the number of semesters it takes will depend on the preparedness of the students as much as the coursework that is offered.

According to Princeton's Office of Health Professions Advising, undergraduate biochemistry is already a requirement at 22 allopathic medical schools and is recommended by 91 [9]. With biochemistry joining the disciplines tested in the 2015 MCAT, it seems extremely likely that essentially all allopathic medical schools will require biochemical coursework for their entering class of 2016. However, achieving the aims of the required coursework is more than checking a box. In my view, students who take an organic chemistry course, which focuses on biochemical reactivity, and who take a biochemistry course, which builds on chemistry, will perform much better than students who take courses that do not specifically try to build interdisciplinary knowledge.

Until life-oriented organic chemistry is a routine offering, I do not expect that medical schools will require students to have the ASBMB-recommended preparation. I expect them to require either the traditional chemistry courses plus coursework in biochemistry or the ASBMB-recommended preparation. Thus, as colleges and universities begin to roll out life-oriented organic chemistry courses and students begin to have the ASBMB-recommended preparation, it will be important to assess how well these students perform in medical biochemistry compared to those with the traditional sequence of general and organic chemistry plus a biochemistry course. In addition, undergraduate biochemistry faculty will be able to assess the performance of students coming in with traditional organic chemistry versus students coming in with life-oriented organic chemistry.

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