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The Future of Undergraduate Immunology Education: Can a Comprehensive Four-Year Immunology Curriculum Answer Calls for Reform in Undergraduate Biology Education?

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ABSTRACT

The field of immunology is rapidly evolving and has significant relevance to understanding human health, particularly in light of the threat from infectious diseases and the ability to harness the immune system to treat cancer, autoimmune diseases, and allergies. Providing opportunities to explore the field of immunology is relevant to undergraduate students interested in pursuing careers in health professions and biomedical research. There are calls for greater emphasis on interdisciplinary science education at the undergraduate level and the acquisition of transferrable competencies that will prepare undergraduates for success in a range of careers. The study of immunology provides an ideal platform to expose students to interdisciplinary science, both at the foundational and applied level. We describe the organization of an immunology curriculum, development of program learning objectives, selection and mapping of content objectives across courses, and programmatic assessment with the intent to meet calls for reform in undergraduate biology education. *ImmunoHorizons*, 2020, 4: 745–753.

INTRODUCTION

The immune system is a complex network of soluble mediators, cells, tissues, and organs that work together to generate and regulate responses necessary to protect us from infectious pathogens that cause disease. Understanding how the immune system functions is also critical for appreciating the etiology, progression, and treatment of a wide range of diseases. Thus, a case can be made that teaching immunology at the undergraduate level is appropriate to ensure that we have a cadre of knowledgeable individuals who go on to pursue careers in healthcare and research. However, research has demonstrated that the immune system is far more intricate than first realized and highlights the interdisciplinary nature of the field of immunology. The immune system interfaces with all other organ systems in the body, intimately linking it to several physiologic processes that regulate health and disease. Understanding how components of the immune system are generated and the basis of immune responses requires an understanding of concepts in many scientific disciplines, including molecular and cellular biology, genetics, chemistry, and biochemistry. Understanding how components of the immune system influence physiologic processes and provide protection from disease requires application of knowledge in additional subjects such as microbial pathogenesis, anatomy, and physiology. Finally, learning about the immune system is analogous to learning a new language composed of complex terminology and conceptual paradigms. Comprehending this information and its complexities is unlikely to be accomplished in a single course or even in a track within a major because of the time needed for students to be able to learn core concepts and then apply that knowledge using higher-order thinking. This reality supports the need to develop comprehensive, four-year educational programs at the undergraduate level to provide students with an in-depth exposure to

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Abbreviations used in this article: CURE, course-based undergraduate research experience; VALUE, Valid Assessment of Learning in Undergraduate Education.

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both the normal as well as the pathophysiological aspects of the immune response.

Interdisciplinary science and undergraduate education

In addition to the inherent relevance of immunology for understanding host defense and immune-mediated disease processes, the focus on developing comprehensive undergraduate curricula in immunology addresses the call for reform in biology education. Numerous reports have called for reform in undergraduate biology education and have focused on the acquisition of various competencies in the biological sciences at the undergraduate level. These competencies include an appreciation of the interdisciplinary nature of science and scientific literacy and are important to ensure the success of graduates who subsequently pursue professional or graduate school. At the same time, efforts to ensure that graduates have acquired a range of transferrable competencies to facilitate their ability to succeed in a variety of career paths and to ensure that they have the ability to quickly adapt to the changing labor market because of sociological and technological advances have been called for (1–5). As noted above, recommendations for reform from these reports have been largely focused on the integration of knowledge across scientific disciplines. In 2003, the National Research Council proposed that biology majors need to acquire stronger foundations in core subjects and interdisciplinary problem-solving abilities and that changes in teaching and learning must be made to better engage undergraduate students (2). In 2009, the Association of American Medical Colleges and Howard Hughes Medical Institute recommended the development of more interdisciplinary and integrative courses in the undergraduate science curriculum (5). These calls for change, in addition to others, led to the development of Core Competencies and Disciplinary Practice outlined in "Vision and Change in Undergraduate Biology Education" (1). The ability to tap into the interdisciplinary nature of science is one of the six core competencies that are described.

Interdisciplinary education involves instructional methods built around common themes that can be studied from the perspective of multiple disciplines (6, 7). Similarly, interdisciplinary science education enables practitioners to provide contextual insights from multiple scientific disciplines that are distinct but complementary, enabling students to solve complex problems. Integrated science curricula can take many forms, but ideally, courses and programs that provide opportunities for students to merge knowledge and methods from multiple disciplines and subsequently apply that information to understand a subject more deeply or solve a complex problem successfully demonstrate the goal of integrated scientific learning (6).

Immunology offers an ideal platform for interdisciplinary science education at the undergraduate level

The historically siloed nature of undergraduate science majors has presented a number of challenges in generating authentic interdisciplinary opportunities. There are, however, disciplines that can be considered inherently interdisciplinary because of the complexity of their subject matter. Neuroscience and immunology are both disciplines that study complex systems comprising networks of organs, tissues, cells, and molecules that interface with all other organ systems in the body. Both the nervous system and the immune system play critical roles in maintaining normal physiologic functions that contribute to health, while also requiring strict regulation to avoid pathophysiologic states that contribute to disease. Understanding the components of these systems, their functions, regulation, and integration with other systems in the body requires students to access knowledge gained in several other scientific disciplines. As students begin to learn about the foundational principles underlying the normal function of the immune system, they must draw upon chemistry, biochemistry, genetics, and molecular and cellular biology to understand how the immune system develops, functions, and is regulated. As students begin to apply their understanding of the fundamentals to host–pathogen interactions and immune-mediated diseases, they will have to incorporate principles from anatomy, physiology, pathology, and microbiology to fully appreciate how the immune system regulates health and disease. Importantly, one can also demonstrate interdisciplinary connections between engineering, physics, chemistry, and the quantitative sciences, including statistics and bioinformatics, with the study of immunology, both at the foundational and applied levels.

In contrast to the widespread availability of undergraduate neuroscience programs offered by academic institutions in the United States, there are only a handful of comprehensive programs in immunology (8). Although immunology education has historically been reserved for the graduate level, the rapid expansion of discovery in the field of immunology and application of this knowledge has increased the demand for individuals who possess an in-depth understanding of the immune system. As interest in undergraduate immunology education grows, we propose that the creation of undergraduate immunology programs can address the calls for reform in undergraduate biology education and foster the acquisition of competencies that extend beyond discipline-specific knowledge. In this perspective, we describe the creation of a model undergraduate immunology curriculum and outline a plan to map foundational and applied content in immunology across five core courses. Additionally, we discuss the interdisciplinary nature of immunology and provide a framework for program assessment to evaluate acquisition of core knowledge and transferrable competencies as well as the ability to apply the knowledge, skills, and attitudes in an interdisciplinary manner.

CURRICULUM DESIGN

Identification of program learning outcomes

In this age of rapidly expanding knowledge in scientific fields and the accumulation of vast amounts of information that is readily available because of technological advances, teaching students in an accessible way that fosters development of critical thinking, problem-solving, analytical, and communication skills is as important as teaching specific content within a given scientific discipline. For the development of a comprehensive undergraduate immunology

curriculum that would teach students in an accessible way and develop necessary competencies, we propose the use of a backward design approach. The backward design approach, also referred to as "understanding by design," first identifies the desired knowledge and competencies of students, which are then used to guide the development of instructional methods and forms of assessment (9). This design strategy has been used to successfully guide a variety of educational science curricula, from the development of physiology lessons (10) and introductory biology courses (11) to the creation of nutrition programs (12) and comprehensive curricula for neuroscience (13, 14) and nursing (15, 16), among many others.

Drawing on our experience in immunology education at all levels, we propose the following would be desired attributes of graduates from an undergraduate immunology program: 1) understand the interdisciplinary nature of science, 2) demonstrate scientific literacy, 3) appreciate the role of the immune system in health and disease, and 4) develop transferrable competencies necessary for success in biomedical careers.

Following the backward design strategy, we propose the following program learning outcomes for a comprehensive undergraduate immunology curriculum, which are derived from the desired attributes of graduates of the program: 1) acquire knowledge of the immune system and apply it in an interdisciplinary framework, 2) develop critical thinking and problem-solving skills, 3) develop scientific inquiry and quantitative reasoning skills, 4) communicate effectively orally and in writing, 5) work well as part of a team, and 6) behave professionally and ethically. Identification of the program learning outcomes provides a framework in which the development of assessment strategies, instructional methods, and learning activities can occur in both classroom and research settings (Fig. 1).

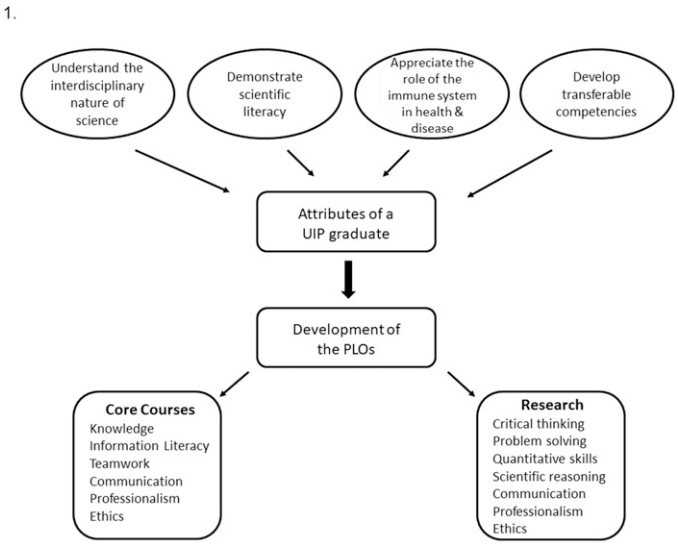

FIGURE 1. Overview of the backward design approach for creating the curriculum infrastructure to support learning outcomes. Identification of the attributes desired in graduates of an undergraduate immunology curriculum directs the creation of the program learning outcomes (PLOs) and subsequent development of educational activities and assessments that demonstrate the development of competencies as students progress through the program.

Organization of the core immunology content

The complex and interdisciplinary nature of immunology, coupled with rapid expansion of information in the field, requires careful thought with regard to the selection and delivery of the discipline-specific, interdisciplinary, and competency-based content. As envisioned, the core curriculum would consist of a sequence of courses that delve into foundational and applied concepts pertaining to the immune system while using teaching pedagogies that foster the development of competencies identified in the program learning outcomes. Ideally, this sequence of courses would begin in the second term of the sophomore year. However, because immunology is not widely taught at the high school level, we argue that it is beneficial to create one or more introductory, one credit-hour seminars or colloquiums that can be used to introduce freshmen to critical concepts in immunology and that provide an overall context for the important role that the immune system plays in health and disease (Table I). Such introductory courses should be designed to build community among students in the major and introduce students to current topics in immunology, ongoing research into the immune system, and how knowledge of the immune system can be used to diagnose and treat disease. An example would be a course that provides a historical overview of important topics in immunology such as vaccines, emerging infectious diseases, autoimmunity, transplantation, and immunotherapy. Complementary courses could revisit these or similar topics but with a focus on how biomedical research into the immune system generates novel information that can be harnessed to develop diagnostics and therapeutics to improve health and treat disease. Importantly, although these introductory courses are important for fostering a community of engaged students, which is critical for building a program, these courses could be adapted to meet core curriculum requirements for other majors, thus reaching a broader audience.

Following the introductory courses, we propose a sequence of five courses that comprise the "core" courses of the major (Table I). Core courses would focus on building foundational knowledge in immunology while reinforcing and applying concepts from other scientific disciplines. Recommendations regarding immunology content at the undergraduate level have not been addressed in the field. Thus, the proposed content for a comprehensive immunology curriculum was identified by a group of faculty in the Department of Microbiology at the University of Alabama at Birmingham that are actively engaged in education at several levels. The contributing faculty reached consensus on 10 content objectives (Table II) and a corresponding list of subtopics (Supplemental Material). The content subtopics were then mapped into the five core courses of the major (Supplemental Material).

Recognizing the density and breadth of information in the field of immunology, we propose the use of a "bull's-eye" approach for framing content delivery through the core courses of the major.

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TABLE I. Core science courses in the immunology major

Year 1		Year 2		Year 3		Year 4	
Fall	Spring	Fall	Spring	Fall	Spring	Fall	Spring
Introduction to Chemistry I	Introduction to Chemistry II	Introduction to Biology II	Organic Chemistry II	Physics I	Physics II	Microbial Pathogen–Immune System Interaction	Immune-Mediated Diseases
Calculus I	Introduction to Biology I	Organic Chemistry I	Genetics	Fundamentals of Biochemistry	Biostatistics		
	Current Topics in Immunology	Seminars in Immunology	Biology of Microorganisms	Foundations in Immunology: The Innate Immune System	Foundations in Immunology: The Adaptive Immune System		
			Introduction to the Immune System				
			Recommended time frame for research (minimum of two semesters)				

This is a recommended academic plan for alignment of science courses and immunology core courses across a four-year curriculum.

This approach requires the identification of core topics that form the foundation to which contextual and application-based information can be added and expanded upon in subsequent courses (Fig. 2). Employing the bull's-eye approach would provide students with complementary, iterative exposure to core topics throughout the curriculum to reinforce their comprehension and retention of the information, which is arguably complex in nature. As an example of this approach, core topics pertaining to both innate and adaptive immunity would be covered in the first course in the core sequence (sophomore year). These core topics would then be reinforced in two subsequent courses (junior year) that specifically delve into the innate and adaptive arms of the immune system by revisiting the core topics in greater detail and in differing contextual frameworks, as outlined in the content subtopics map (Supplemental Material). Last, application of the core topics would be accomplished in the final two courses of the sequence (senior year) through the introduction of information pertaining to the nature of the immune response to specific classes of pathogens as well as concepts focused on how dysregulation of the immune system leads to immune-mediated diseases and how the immune system can be harnessed to treat disease. Importantly, in the field of immunology, an assessment of the inclusion of specific immunology topics in introductory courses at the undergraduate level has yet to be undertaken, nor has consensus regarding perceived core topics in the field been confirmed. Thus, in employing the bull's-eye approach to structure the content delivery in the curriculum, the core topics identified (Table III) were selected because they facilitated the most appropriate delivery framework for this comprehensive curriculum.

Programmatic assessment

Assessment, curriculum, and instruction are central to educational practice, and alignment of these components is critical to ensure an effective learning environment across a program (17, 18). The inclusion of proper forms of assessment in the curriculum can promote learning by providing impactful pedagogical experiences (19). Furthermore, knowing whether students are able to transfer and apply core knowledge learned in one disciplinary course to another or in an interdisciplinary context provides information about the effectiveness of the curriculum as a whole (20). Following the backward design approach, forms of assessment should be selected that can provide evidence of achievement of the identified program learning outcomes (9). Assessment maps can provide structure and continuity in the selection of assessments for individual courses, as well as across the program, to gauge the attainment of learning goals by students as they progress through the program. Based on the program learning outcomes discussed above, the assessment map detailed in Table IV demonstrates a comprehensive plan for evaluating attained competencies within courses and across the program.

Programmatically, we propose that assessment of student acquisition of knowledge could be evaluated through the administration of a multiple choice content examination at the start of the introductory course in the core sequence and again at the end of the final course in the core sequence. The mapping of content subtopics to the core courses (Supplemental Material), along with the bull's-eye approach employed in developing content delivery within the curriculum, would provide a structure with which to align the delivery of information with the assessment of student understanding and application of knowledge according to the revised Bloom's Taxonomy (21).

In addition to assessing acquisition of knowledge, we propose the inclusion of assessments throughout the curriculum, across multiple courses that provide evidence of student progress in developing competencies. As an example, group presentations, a form of assessment addressing the development of communication skills, are included across three courses (Table IV). Although grades within a course are an indicator of achievement, they fall short of demonstrating the development of skills across a curriculum, such that students may earn an A for a presentation

TABLE II. Content objectives of the curriculum

Program Content Objectives
Introduction to immunology
Innate immune responses
Lymphocyte development and activation
Humoral and cell-mediated immune responses
Mucosal immunity
Immunopathologies
Immunodeficiencies
Infectious disease and vaccines
Immunologic methods and experimental systems
Immunotherapies

The content objectives identify the principal subject areas covered in the core course sequence.

in a 200-level course, although they most likely have not fully mastered oral communication. Thus, assessment tools, such as the Valid Assessment of Learning in Undergraduate Education (VALUE) rubrics, should be considered. These rubrics were developed by teams of faculty and educational professionals because of efforts led by the Association of American Colleges and Universities and provide a method of assessing the developmental progression of student accomplishment, culminating in advanced and integrative learning (22). By implementing assessments involving oral presentations in multiple courses in the core sequence and using the Oral Communication VALUE Rubric (23), student progress in developing oral communication skills can be evaluated as the student gives subsequent presentations while progressing through the core sequence.

The selection and use of assessments within courses and across the curriculum determines a path for the development of learning activities and instructional methods that are centered around the core immunology content and will help students achieve the learning outcomes of the program. In addition to traditional lectures, we envision the incorporation of several different educational activities. These could include but certainly are not limited to information literacy learning exercises, team-based activities or collaborative concept mapping, case studies, and problem-based learning. The inclusion of a broad range of learning activities and educational modalities is essential to ensure that students not only master the discipline-specific content related to understanding the immune system but also so that they have varied opportunities to acquire the broad range of transferrable competencies that they will need for success at the next level.

Opportunities for interdisciplinary learning in the immunology curriculum

As noted previously, there have been numerous calls for an increased emphasis on the interdisciplinary nature of science at the undergraduate level. Indeed, this parallels the more recent evolution of convergent science, in which knowledge and technologies from distinct scientific disciplines are harnessed to solve a specific problem. Education in immunology provides an ideal focus that can be used to introduce students to interdisciplinary concepts in science, regardless of whether one is talking about foundational or applied information. Ironically, this is perhaps one of the reasons that education in immunology has traditionally been limited to the graduate and professional levels; it is the inherent belief that students must have a foundational understanding of a number of other scientific disciplines before they can effectively understand how the immune system works. We argue that this is not the case and that undergraduates can be taught immunology in a context that reinforces their understanding and appreciation of other scientific disciplines while at the same time mastering foundational knowledge of the immune system.

There are numerous examples that one can cite to reinforce this perspective, regardless of whether one is focused on teaching undergraduate students about foundational or applied information pertaining to the immune system. At the foundational level, for example, when talking about trafficking of immune cells in the body, one can reinforce principles of cell biology, biochemistry, physiology, and anatomy in a single lecture. Teaching students about the mechanisms used to generate diversity in the T and B cell AgR repertoire provides an ideal opportunity to introduce concepts in genetics, cell biology, and biochemistry. Another concrete example of the interdisciplinary nature of immunology can be provided by teaching students about flow cytometry, which is one of the most important tools used to study the immune system and is also used in diagnostic and therapeutic settings. Flow cytometry encompasses principles that draw upon biology,

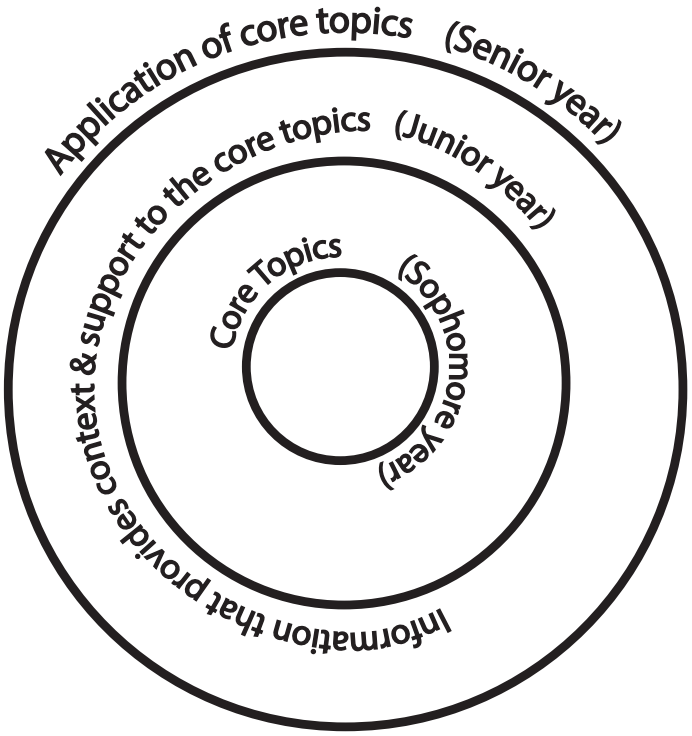

FIGURE 2. The bull's-eye approach for framing content delivery in the curriculum.

Core topics form the basis of content knowledge within the curriculum, which is then expanded upon and applied as students progress through the core course sequence.

TABLE III. Topics covered in the core courses of the immunology major

Introduction to immunology
Basics of hematopoiesis
Categories of cell types, characteristics, and functions
Anatomy of the lymphoid organs and tissues
Trafficking of leukocytes throughout the body
Properties of receptor–ligand interactions
Characteristics of signaling molecules and tyrosine-dependent pathways
Innate immune responses
Functional elements: barriers, cells, tissues, and soluble mediators
Characteristics, functions, and activation mechanisms of innate immune cells
Pattern recognition receptors, pathogen/damage–associated molecular patterns
Mechanisms of extravasation, phagocytosis, and pathogen destruction
Function and components of the inflammatory response
Activation and functions of the acute phase response
Activation, regulation, and functions of the complement system
Cooperation of complement and the inflammatory response in the elimination of pathogens
The role of NK cells and the IFN response in eliminating viral pathogens
Processes performed by innate immune cells that result in the activation of the adaptive response to a pathogen
Lymphocyte development and activation
Functional components of lymphocyte AgR
Organization and expression of lymphocyte AgR genes
BCR and TCR gene rearrangements
Processes of B and T cell development from a stem cell to a mature cell
Structure, function, and expression patterns of classical MHC molecules
The role of APC and Ag processing and presentation pathways in T lymphocyte activation
Mechanisms of B cell activation by T-independent and T-dependent Ags
Ab structure, structural isoforms, isotypes, and Ag–Ab interactions
Humoral and cell-mediated immune responses
T-independent B cell responses
T-dependent B cell responses, linked recognition, generation of high-affinity Ab production, and class switching
Ab-mediated effector functions
The role of APC and cytokines on the differentiation of T cell subsets
$CD4^+$ T cell–mediated functions
$CD8^+$ T, NK, and NKT cell functions
Characteristics and function of memory responses

The core topics that form the basis of the content delivery frame are listed in this table.

chemistry, physics, engineering, mathematics, statistics, and bioinformatics. Teaching students about flow cytometry (24–26) provides an excellent example of the importance of convergent science to create a technology that has widespread application to the field of immunology and to medicine. Moreover, understanding the principles of flow cytometry provides an opportunity for students to learn about related technologies, including mass cytometry (27–29) and imaging flow cytometry (ImageStream) (30, 31) that, in turn, can be used to introduce students to other related imaging technologies that are used not only for basic research but also for diagnosis and treatment of disease. It is important to note that, as technology changes, it may be necessary to revise the curriculum to reflect advances made in a specific technology or to present new technologies that may be covered to more effectively demonstrate the interdisciplinary nature of science. Finally, when talking about immune-mediated diseases, it is possible not only to discuss how dysregulation of normal physiological processes can lead to disease but also to present concepts related to the use of core scientific knowledge for the development of diagnostics and therapeutic interventions to detect and cure disease. As an example, when teaching students about immune-mediated diseases, such as systemic lupus erythematosus, one can draw connections between genetics, microbiology, environmental science, and pathophysiology to explain the etiology and progression of the disease as well as to present the mechanisms by which dysregulation of the immune system drives the disease process. In conclusion, the study of the immune system provides numerous opportunities to promote interdisciplinary science education for students at the undergraduate level, albeit with the challenge that it requires a fairly high-level understanding of core concepts in various scientific disciplines.

Development of scientific literacy and inquiry through research experience

As noted above, numerous reports have called for an enhanced emphasis on providing opportunities to students that teach them about scientific inquiry or the scientific method. Toward that goal, undergraduate research opportunities reinforce concepts taught in the classroom while also providing a context in which to apply that information while learning about the scientific process. The skills, knowledge, and attitudes associated with an appreciation of the scientific process can be provided via a number of approaches, but one of the most effective is through student-driven,

TABLE IV. Assessment map for the immunology major

		Core Course Sequence					
Program Learning Outcomes	Assessments	Introduction	Innate	Adaptive	Host–Pathogen	Immune Disorders	Research
Acquire appropriate content knowledge							
	Content examination	X				X	
Communicate effectively							
	Presentations (VALUE rubric)	X	X	X			
	Written reports (VALUE rubric)				X	X	
	Research project thesis						X
	Research project presentation						X
Work well as part of a team							
	Group presentations	X	X	X			
	Team-based learning activities		X	X			
Develop problem-solving, critical thinking, scientific inquiry, and quantitative reasoning skills							
	Information literacy assignments	X	X	X			
	Data analysis assignments		X	X			
	Research						X
Behave professionally and ethically							
	Class attendance and participation	X	X	X	X	X	
	Conduct in research training						X

Recommended assessments in the core courses of the major aligned with the program learning outcomes.

inquiry-based, undergraduate research opportunities (32–34). Concepts are best understood by students when they are given the opportunity to apply them in real-life settings (35, 36). Furthermore, undergraduate research opportunities can promote the development of competencies such as critical thinking and problem-solving (37, 38). Ideally, students should have access to a course(s) that provides an overview of the following topics: the scientific process, how to access the scientific literature and use databases, procedures for recording and storing experimental data, and research safety. Exposure of students to such topics prior to undertaking an independent research project is essential for ensuring that students are prepared to gain the maximum benefit from the experience. Undergraduate research also provides numerous opportunities to teach students about the ethical conduct of research, rigor and reproducibility, and personal responsibility with respect to how one is supposed to conduct themselves in professional settings. These competencies can be assessed to ensure that students have mastered the requisite knowledge, skills, and attitudes. Accordingly, we propose that a comprehensive immunology curriculum would have embedded within it the requirement that students engage in a hands-on research experience. Where opportunities and resources are available, we would propose that students work on an independent research project within a laboratory across a minimum of two semesters (credit hours totaling 6–10 h per semester) any time during the sophomore, junior, or senior year (Table I) and engage in laboratory meetings and journal clubs.

However, we recognize institutions often have limited resources, and demand for undergraduate research experience can exceed departmental capacity. An alternative option may be course-based undergraduate research experiences (CUREs), which allow students exposure to a variety of research methods. An increasing number of CUREs have demonstrated student learning gains and the development of competencies similar to students conducting independent research projects within a laboratory (39–41). Furthermore, CUREs can also reinforce interdisciplinary learning (42, 43). Last, class-based learning activities that teach students how to access information through appropriate sources, create effective literature searches, identify relevant articles, and extract information pertinent to answering a question or formulating an idea develop and reinforce scientific information literacy skills.

Although the type of research experience may vary, the purpose for including an undergraduate research experience in the curriculum is to provide students with exposure to cutting-edge research in immunology that fosters the acquisition of critical thinking, problem-solving, quantitative and analytical skills, and enhances communication skills, both orally and in writing, and to again demonstrate the importance of interdisciplinary scientific principles for the discovery and application of new knowledge (36, 44–46).

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DISCUSSION

In this essay, we outline a model for the development of a four-year comprehensive undergraduate immunology major. Although training in immunology has historically been done at the graduate level, calls for reform in undergraduate biology education have focused on interdisciplinary learning, acquisition of scientific literacy, and the development of transferrable competencies. The emphasis on these important outcomes, coupled with an increased need for individuals with specialized knowledge of the immune system, have intensified the exploration of immunology education at the undergraduate level. We propose that the creation of specialized majors in immunology meets a critical need to provide interdisciplinary science education with an in-depth focus on the immune system and that such majors can also foster the development of critical thinking and problem-solving, as well as quantitative and analytical skills, and generate well-rounded graduates who have the necessary attributes to succeed in a range of careers in the biomedical sciences.

As noted previously, several reports have called for a focus on interdisciplinary science education (1, 2, 20) to foster an appreciation of the interrelationships between different scientific disciplines and the important role that convergent science plays in not only the discovery of new knowledge, but also in the application of knowledge for the development of new technologies and, in the healthcare arena, the development of novel diagnostics and therapeutic interventions. A major impetus for creating a new major that focuses on immunology is the fact that understanding the immune system inherently relies on knowledge in a number of other scientific disciplines, including cellular and molecular biology, genetics, biochemistry, physiology, anatomy, and microbiology. This fact presents both a challenge and an opportunity when developing a curriculum that is focused on the immune system at the undergraduate level. The challenge is that students need to have an introduction to basic principles from several scientific disciplines and to understand the fundamental paradigms associated with each discipline to fully comprehend what the immune system is and how it functions. The introduction of immunology topics early in the undergraduate educational timeline likely would occur at a point when many key principles in science are converging in the minds of science majors. Thus, although it is a challenge to teach concepts pertaining to the immune system that require application of knowledge from broad scientific disciplines, it is also a significant opportunity to reinforce the application of that knowledge in the context of immunology.

Although we foresee an undergraduate immunology major meeting the needs of talented, highly motivated students who desire careers in the health professions and research and who will likely pursue advanced education in professional and graduate school settings, there may be institutional settings in which such a program cannot be replicated, and there may be students with diverse interests who want to get exposure to immunology but not dedicate themselves to a major with an intensive focus on the immune system. Furthermore, there are many ways that concepts in immunology can be combined with other scientific disciplines from a curricular standpoint that may dictate the need for a different overall curricular design. For example, the relevance of immunology to public or global health is readily apparent and might require specific considerations for curricular development. Other examples include the potential relationships between evolutionary biology, bioinformatics, or environmental ecology and immunology. Thus, different institutions or programs may choose to develop immunology curricula that have unique foci that go beyond what has been proposed in this work. Clearly, there are several factors that drive course development and content selection at any institution, and as a result, there is no singular way of teaching immunology at the undergraduate level.

CONCLUSIONS

Calls for reform in undergraduate biology education include increased emphasis on the interdisciplinary nature of science. Although training in immunology has historically been reserved for the graduate level, the inherently interdisciplinary nature of immunology may make it an ideal platform for interdisciplinary science education at the undergraduate level. The intent of describing the components of a proposed undergraduate immunology curriculum in this essay is to provide a resource for undergraduate educators that can be broadly applied within a variety of programmatic contexts. Additionally, it is hoped that it will foster dialogue among educators in the immunology community that leads to the establishment of effective mechanisms for communication and collaboration that facilitate the development of additional comprehensive, undergraduate immunology programs at other institutions. Moreover, by bringing together a community of immunology educators, the intent is to provide a way to continually refine these curricula over time, based on the use of assessment to create validated, evidence-based approaches that can adapt to scientific, technical, and social changes that impact our understanding of immunology as well as novel teaching and learning strategies going forward.

DISCLOSURES

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1. Introduction to Immunology

1.1. A historical perspective of immunology.
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1.3. The anatomy of the lymphoid organs, tissues, and the movement of leukocytes in the body.
1.4. General properties of receptor-ligand interactions.
1.5. Overview of signaling molecules and pathways.

2. Innate Immune Responses

2.1. Overview of the characteristics and functions of the innate immune system.
2.2. Functional elements of innate immunity: barriers, cells, tissues, soluble mediators.
2.3. Pattern recognition receptors, pathogen (damage)-associated molecular patterns.
2.4. Activation of innate immune cells and signaling pathways.
2.5. Mechanisms of extravasation, phagocytosis, and pathogen destruction.
2.6. Function and components of the inflammatory response and the subsequent outcomes of localized and systemic inflammation.
2.7. Acute phase response and the resulting systemic changes in the body.
2.8. Complement system components, activation and regulation of the complement system and its role in the recognition and elimination of pathogens, cooperation with the inflammatory response and hemostatic/coagulation pathways.
2.9. The role of NK cells and interferons in the recognition and elimination of virally-infected cells.
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2.11. Processes performed by innate immune cells that result in the activation of T and B lymphocytes to a specific pathogen.

3. Lymphocyte Development and Activation

3.1. Organization and expression of lymphocyte receptor genes.
3.2. Discriminate between BCR and TCR gene rearrangements, functional parts of each receptor, cell signaling events through these receptors, and cell surface marker expression during development and on mature lymphocytes.
3.3. B and T cell development from a stem cell to a mature cell.
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3.5. Genetic organization of the Major Histocompatibility Complex (MHC) including the concepts of co-dominant expression, polygeny, polymorphism, and linkage disequilibrium.
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4.6. CD4+ T cell-mediated functions.
4.7. CD8+ T, NK, and NKT functions.
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4.9. Characteristics and function of memory responses.

5. Mucosal Immunity

5.1. The cells and tissues of the mucosal immune system, with emphasis on the gastrointestinal tract.
5.2. Prominent species of the human microbiome and the contribution of non-bacterial species to the microbiome: mycobiome and virome
5.3. The ability of the mucosal immune system to switch from a tolerant response to an active immune response against pathogens
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6. Immunopathologies

6.1. Hypersensitivities
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6.2.1. Immune dysregulation and chronic inflammation, causes and consequences
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6.3.1. Mechanisms of central and peripheral tolerance.
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8.11. Protective immunity through passive and active immunization.
8.12. Characteristics, strengths and weaknesses of varying vaccine strategies. Memory responses and original antigenic sin.

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9.5. Flow cytometry and cell sorting.
9.6. Use of mouse model systems – inbred and congenic strains, adoptive transfer experiments, transgenic mice: knock-in, knockout, cre/lox systems

10. Immunotherapies

10.1. History of development
10.2. Activating immunotherapies
10.3. Suppressive immunotherapies

401 – INNATE IMMUNITY

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402 – ADAPTIVE IMMUNITY

Brief review of 2.1, 2.3, 2.11

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403- PATHOGEN-IMMUNE SYSTEM INTERACTIONS

Review 2.5 – 2.9
Review 3.8, 3.9
Review 4.4, 4.6, 4.7, 4.9

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404 – IMMUNE-MEDIATED DISEASES

Review 4.8
Review PLO 9

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