Although immunological research has become increasingly important in recent decades for understanding infectious and immune-mediated diseases, immunological pedagogy at the undergraduate level has lagged behind in reports of evidence-based scholarship. To address the need for a renewed emphasis on immunology education and to describe the current status of undergraduate education in immunology, an online survey of instructors with experience in teaching immunology was conducted. The survey investigated the effects of instructors’ level of teaching experience, target student population, and course components on the emphasis given to certain immunology subtopics in their courses. Instructor teaching experience and current role in teaching influenced the proportion of time allotted to lab techniques, clinical topics, and evolutionary aspects, but type of institution (undergraduate and graduate degree-granting institutions) did not affect course content or emphasis on subtopics. Topics that received the greatest emphasis were the adaptive immune system, the innate immune system, host-pathogen interactions, and molecular mechanisms. Vaccines, hypersensitivity, autoimmunity, and essential immunology techniques were ranked slightly lower, while topics such as evolution, metabolism and antibody purification received the least emphasis. Inclusion of a lab component increased time given to lab-related and clinical topics but did not affect the perceived importance of various scientific competencies. These data describe current curricular practices of instructors who have experience teaching immunology and inform curricular priorities and course design frameworks for undergraduate immunology education.

INTRODUCTION

The field of immunology is rapidly expanding, highlighting the importance of immune function and regulation in all aspects of health and disease, as well as underscoring the relationship between the immune system and other scientific disciplines, such as ecological sciences (1) or evolutionary biology (2). Advances in other fields, including genetics, biochemistry, and bioinformatics, are actively transforming the field of immunology, as evidenced by a rapid surge in publications related to immunometabolism (3), systems immunology (4), and disease modeling (5). Incorporating this large amount of information into undergraduate curricula and summarizing it is without question a daunting task. Although research has rapidly advanced knowledge of immune function in diverse contexts, deciding which concepts to include in undergraduate curricula is often overwhelming and is further exacerbated by limited and inconsistent inclusion of immunology in introductory science courses (6) or even semester-long courses in biology programs (7).

As noted, at the undergraduate level, the introduction of concepts pertaining to the immune system is often limited to a single semester course or a single unit in a related course such as Microbiology or Anatomy and Physiology, and the selection of topics is frequently based on one or more factors, including covering topics in textbooks (8), research or review papers (9), time-honored traditions, time-dependent needs of the curriculum within an institute/
department, or the individual interests or expertise of an instructor (10). There are few resources available to undergraduate immunology educators to guide content selection and development of immunology-centric instructional materials (11). Importantly, development of common standards for concepts and topics taught in a course has a positive impact on student learning experience and performance (12–14). Although the importance of establishing core concepts to assess student understanding has been highlighted in disciplines such as physiology (15, 16), microbiology (17, 18), and neuroscience (19), the evaluation of core concepts for undergraduate immunology has only just begun (20). Moreover, immunology education as a whole has not established itself as a programmatic discipline at the undergraduate level, in contrast to the discipline of neuroscience, which is taught extensively (11). Neuroscience and immunology share the common characteristic of being systems that extend throughout the body and interface with every other system in the body. Thus, these disciplines have tremendous potential for introducing students to interdisciplinary scientific concepts. However, at the same time, the ability to do so effectively is highly dependent on identifying foundational core concepts that must be understood in order to then apply that knowledge in an interdisciplinary manner.

Evidence-based curriculum development is a multi-step process that involves an assessment of current curricular practices to determine the content and learning outcomes commonly used, so that going forward, appropriate teaching activities and validated assessment tools (e.g., concept inventories) can be designed and aligned for maximal effectiveness (21). An excellent example of this process in the field of undergraduate microbiology education involved a rigorous process in which educators first identified core concepts, fundamental statements, and learning outcomes, which then aided the development of a validated assessment tool to create more robust and reproducible educational resources for the community (22, 23). Additionally, to help with curriculum development, many educators and professional discipline-specific societies have laid out course-design frameworks based on the backward-design or integrated-course design approach (24, 25). For a highly conceptual, interdisciplinary, and rapidly-changing discipline like immunology, the enormity of identifying core concepts can be overwhelming (26–28). To begin to address this challenge, a consortium of educators who teach immunology at the undergraduate level and who are familiar with undergraduate curricular practices undertook the first organizational initiative to solicit feedback from the educator community regarding the topics that professional instructors of immunology courses prioritize. This initiative was based on previous research demonstrating that the quantity of instruction/amount of time spent by an instructor on a topic has a significant impact on student learning (29). Towards this goal, immunology educators were asked to reflect on the current status of the course(s) they teach in this field and to describe the distribution of time allotted in their course(s) to each of several predetermined subtopics. Data obtained from the survey provided information that was used to delineate factors that potentially influence the time prioritization of topics and importance attributed to skills and competencies in immunology by instructors. The conclusions from this survey serve as a critical first step to ascertain curricular priorities and to design hierarchical content frameworks for undergraduate immunology education.

**METHODS**

**Participants**

A faculty survey (Appendix 1) was developed, using Qualtrics, to gather data on the proportion of time spent on specific topics in immunology during semester-long undergraduate immunology courses. This study was approved by Minnesota State University Moorhead’s IRB protocol #1561719-1. The survey link was distributed to faculty at large, via email, society listservs [Society for the Advancement of Biology Education Research (SABER), American Society for Microbiology (ASM)’s Microedu, Partnership for Undergraduate Life Sciences Education (PULSE), Society for Leukocyte Biology (SBL)], social media (Twitter and Facebook), and word of mouth. Participation was voluntary, and prior to taking the survey, a confidentiality policy was shared with the respondents (Appendix 1). The survey instrument and procedures were reviewed and approved by the Minnesota State University Moorhead Institutional Review Board.

**Survey description**

Data from the survey were organized into four sections. The first section was demographic data, such as highest degree earned, institution type, and years of experience teaching (see Appendix for the complete list). Using a five-point Likert scale, the second section asked respondents to identify the proportion of their courses dedicated to specific topics (pre-selected based on preliminary discussions amongst the authors): i) basic immunology (historical perspective, innate, adaptive and mucosal immunity, molecular mechanisms in immunology); ii) clinically focused topics (vaccines, host–pathogen interactions, autoimmunity, hypersensitivity, transplantation and tumors); iii) lab-based skills in immunology (immunologist’s toolbox [flow cytometry, ELISA, etc.], diagnostics, cell culture and antibody purification); and iv) a category that reflected emerging topics (metabolism and evolution, in terms of immunometabolism and ecoinmunology, respectively).

The third section asked respondents to rate the importance of seven skills for student learning in a laboratory setting, again on a five-point Likert scale. The skills, with abbreviations in parentheses, as are follows: i) Identify and investigate the key elements of an immune response (Key elements); ii) Isolate and identify key cells and tissues
involved in an immune response (Cells tissues); iii) Describe techniques used to measure or identify effector functions of immune components (Effector functions); iv) Explain how antigen–antibody interactions can be used to measure or detect the presence of an antigen (Antigen–antibody); v) Explain how gene expression changes during an immune response to an antigen (Gene expression); vi) Identify methodologies that manipulate the immune system (Manipulate); and vii) Use best practices in an immunological laboratory (e.g., biosafety levels, federal and institutional regulatory protocols, etc.) (Best practices).

Lastly, in the fourth section, respondents were again asked to indicate (using a five-point Likert scale) the importance of the following core competencies identified in the Vision and Change in Undergraduate Biology Education report (13) for student learning in the context of immunology. The competencies, with abbreviations in parentheses, are as follows: i) Ability to apply the process of science (Process); ii) Ability to use quantitative reasoning (Quant Reason); iii) Ability to communicate and collaborate with other disciplines (Comm & Collab); iv) Ability to understand the relationship between science and society (Sci & Society); and v) Ability to use modeling and simulation in immunology (Model & Sim).

Data analysis

Mean ranks of time allocations for each subtopic were compared using a one-way ANOVA followed by Student-Newman-Keuls post hoc pairwise comparisons. Comparisons for the effects of laboratory and instructor teaching experience were compared using independent t-tests. For topics that showed significant differences for courses with and without laboratory components, we tested whether individual respondents on time allocations predicted their subsequent responses to questions about the Vision and Change topics (process of science, communication and collaboration, science and society, quantitative reasoning and modeling and simulation) and laboratory skills (Key elements, Cells tissues, Effector functions, Gene expression, Manipulate, Best practices) using Pearson correlation coefficients. All analyses were conducted using SPSS v26.

RESULTS

Demographics

There were 138 responses to the survey. Of these, 49 did not provide responses beyond the demographics questions. These were considered “nonresponders” and were not included in the data analysis. Of the 89 responders, 96% held a PhD (Fig. 1A), 68% held a tenure-track faculty position (Fig. 1B), 71% were currently teaching or had recently taught a course in immunology (Fig. 1C), and 45% had more than 10 years of experience teaching immunology (Fig. 1D). Respondents represented a variety of institution types: 62% came from institutions that offered masters or doctorate degrees, and 32% were from institutions that were primarily undergraduate institutions (Fig. 1E). Regardless of institution type, 66% of respondents taught courses aimed at an undergraduate audience (Fig. 1F), and nearly half of these courses included a laboratory experience (Fig. 1G).

Geographically, the survey respondents were predominantly located in North America (Fig. 2A), with four on the Australian continent (Fig. 2B), two in Asia, and one in Europe.

Overall trends in proportion of time spent on each topic

The amount of time allocated to topics within immunology could be organized statistically into five groupings (Fig. 3). The cluster that received the most time in immunology courses comprised the topics Adaptive Immune System, Innate Immune System, Host–Pathogen Interactions, and Molecular Mechanisms of Immune Responses. There seems to be general consensus among immunology instructors that these topics are fundamental to understanding immunology.

The second cluster of topics included Vaccines, Immunologist’s Toolbox, Autoimmune Disorders, Hypersensitivity Disorders, Mucosal Immunity, and Diagnostic Tools (Fig. 3). These topics were included in courses by most of the respondents but with less time dedication than topics in the first cluster.

The third tier of topics was composed of Transplantation, Tumor Immunology, and Historical Overview of the field of immunology. The fourth grouping, which received the lowest allocation of time, was the group that contained the topics of Cell Culture, Evolutionary Aspects related to immunology, and Metabolic Demands of the immune system. Antibody Purification stood alone as the topic with the fifth, and lowest, rank with respect to the amount of time allocated to it in immunology courses (Fig. 3).

The topics Innate Immune System and Adaptive Immune System both had means above 3.0 and received the highest rankings of categories within group “a” (Fig. 3A), indicating that respondents spent the most time on those topics. Importantly, the type of institution where survey respondents teach and the student population served by the course had no effect on the proportion of the course spent on selected topics (p > 0.05 for all, data not shown). This suggests that topics being taught at all types of degree-granting institutions are time-prioritized similarly, and there is consensus regarding the topics being taught regardless of whether the course serves primarily undergraduate and/or graduate student population. However, other factors, such as years of teaching experience, current teaching status, and the availability of a lab component, were found to be influential in the time prioritization of topics beyond the Innate Immune System and Adaptive Immune System.
FIGURE 1. Demographic data of survey respondents. The total number of responses as a function of education level of the instructor (A), academic track/job title of the instructor (B), the instructor’s immunology teaching status (C), the number of years the instructor has taught immunology (D), the type of institution at which the instructor teaches immunology (E), the degree program of the students enrolled in the instructor’s course(s) (F), and whether or not the instructor’s course has a laboratory component (G). PD = post-doctoral experience; MSc = Master of Science; “Taught elsewhere” = the instructor does not teach an immunology course but teaches immunology concepts in other courses; “Research only” = the instructor does not teach but is involved in immunology research; Bacc = bachelor degree; y = years.
Role of instructor demographics as influencing factors

Current teachers. Survey respondents currently teaching an immunology course at the time of the survey differed in their pedagogical approach from respondents who were not teaching an immunology course at the time of the survey (i.e., taught immunology in past academic years, teach immunologic concepts in other courses, or have not previously taught but do immunology research) (Table 1). Respondents currently teaching immunology put greater emphasis (p < 0.05) on lab techniques (Immunologist’s Toolbox), Adaptive Immune System, Hypersensitivity Disorders, Tumor Immunology, and Evolutionary Aspects of Immunology than respondents not currently teaching.

Teaching experience. Respondents who have 10 or more years of experience teaching immunology put greater emphasis (p < 0.05) on Host–Pathogen Interactions, Mucosal Immunology, Transplantation, and Evolutionary Aspects of Immunology (Table 2).

Differences in educator response based on whether or not their course was accompanied by a lab experience. Courses with a lab component differed from courses without a lab in the proportion of time spent on certain topics (Table 3). As expected, respondents teaching an immunology course that includes a lab spent more time (p < 0.05) on clinical topics (Diagnostic Tools and Transplantation), and lab techniques (Immunologist’s Toolbox and Cell Culture), while respondents indicated that the least amount of time was spent on Antibody Purification (Fig. 3A), although courses with a lab spent slightly more time on the topic (marginally non-significant p = 0.060) (Table 3). Notably, regardless of whether courses offered a lab or not, the proportion of time spent on other topics was not significantly different.

Importance of various lab-related skills for student learning in the context of immunology

Respondents teaching an immunology course were asked to rank the importance of certain skills for student learning in a laboratory setting. The skills could be statistically organized into three groupings (Fig. 4). The skills deemed most essential for student learning in a lab setting were “Use best practices in an immunology laboratory” and “Explain how antigen–antibody interactions can be used to measure or detect the presence of an antigen.” The second tier of skills included “Identify and investigate the key elements of an immune response,” “Describe techniques used to measure or identify effector functions of immune components,” and “Isolate and identify key cells and tissues involved in an immune response.” Lastly, “Identify methodologies that manipulate the immune system” and “Explain how gene expression changes during an immune response to an antigen” were ranked together as the least important skills for student learning.

Topics directly related to the lab that were given more time by instructors in courses with a laboratory component (Immunologist’s Toolbox, Diagnostic Tools, and Cell Culture), were further investigated for correlation with the ranked importance of skills for student learning in a laboratory setting (Table 4). “Identify and investigate the key elements of an immune response” was positively correlated with high scores for time spent on the Immunologist’s Toolbox, and “Describe techniques used to measure or identify effector functions of immune components” was positively correlated with time spent on both the Immuno-logist’s Toolbox and Diagnostic Tools. Unexpectedly, there was a negative correlation between time spent on Diagnostic Toolsand the ranked importance of “Explain how gene expression changes during an immune response to an antigen.”

FIGURE 2. Geographical distribution of survey respondents. The survey respondents were distributed throughout the world, with most respondents located on the North American continent (A), four respondents located on the Australian continent (B). The latitude and longitude data from Qualtrics survey was used for plotting these maps using Microsoft Excel’s 3D Map feature.
FIGURE 3. (A) Mean (±1 SE) rank of time allocation of curricula to individual subtopics in immunobiology, analyzed by one-way ANOVA followed by Student-Newman-Keuls post hoc pairwise comparisons. Shared letters above bars indicate no significant difference \( (p > 0.05) \). (B) Proportion of rankings for each subtopic. Sample sizes varied slightly among categories: \( n=82 \) (vaccines), \( n=85 \) (historical overview, metabolic demands of the immune system, tumor immunology, evolutionary aspects of immunology, host–pathogen interactions, mucosal immunology), \( n=86 \) (hypersensitivity disorders, immunology-based diagnostic tools, molecular mechanisms of immune responses, transplantation, cell culture, antibody purification), and \( n=87 \) (immunologist’s toolbox, adaptive immune system, innate immune system, autoimmune disorders).
during an immune response to an antigen,” which may be due in part to differences in the types of assays, such that “immunology-based diagnostic procedures” is likely thought to cover serological assays while changes in gene expression are generally thought to be investigated by molecular assays, and are perhaps taught in other molecular biology-focused courses.

Role of Vision and Change core competencies for student learning in the context of immunology

The development of specific competencies that are critical for advancing student understanding and application of science are described in the Vision and Change in Undergraduate Biology Education report (13). Survey
respondents were asked to indicate their perceived importance of these competencies in student learning in the context of immunology (Fig. 5). The ability to apply the process of science was ranked highest in importance, followed by both the ability to communicate and collaborate with other disciplines and the ability to understand the relationship between science and society. The ability to use quantitative reasoning was ranked next, with the ability to use modeling and simulation in immunology ranked the lowest in importance. Further analysis revealed no
significant correlation (positive or negative) of the perceived importance of core competencies and time spent on the lab-related topics Immunologist’s Toolbox, Diagnostic Procedures, and Cell Culture (data not shown). Importantly, although the availability of a laboratory component offered with a course influenced the proportion of time spent on some topics (Table 3), it did not influence the perceived importance of the core competencies (data not shown).

Taken together, these data reveal consensus on some large-picture topics for inclusion in an introductory course in immunology for undergraduates, but significant effects were detected for instructor experience and whether or not the course is associated with a laboratory component.
FIGURE 4. (A) Mean ± SE importance of skills for student learning in a lab setting on a scale from 1 (not at all important) to 5 (extremely important). Shared letters above bars indicate no significant difference \((p > 0.05)\) by Student-Newman-Keuls post-hoc pairwise comparisons. (B) Breakdown of rankings by category. Categories (skills) include: i) Use best practices in an immunology laboratory (Best practices); ii) Explain how antigen-antibody interactions can be used to measure and detect antigen (Antigen-Antibody); iii) Identify and investigate the key elements of an immune response (Key elements); iv) Describe techniques used to measure or identify effector functions of immune components (Effector functions); v) Isolate and identify key cells and tissues in the immune system (Cells Tissues); vi) Identify methodologies that manipulate the immune system (Manipulate); and vii) Explain how gene expression changes during an immune response to an antigen (Gene expression). Sample sizes, \(n=58–60\).
DISCUSSION

The identification of core topics is essential for establishing a foundation upon which to build a course. In any discipline, the identification of core topics can be difficult, but especially so in fields with rapid expansion of information or those with complex subject matter that requires multi-disciplinary knowledge. An important first step in this process is the assessment of valued content by practicing educators in the field. Immunological training has historically been reserved for the graduate level, and as such, there has yet to be significant discussion or consensus among immunology educators about core topics to form the foundation of undergraduate introductory or advanced, topic-specific courses in immunology. This study sought to identify and describe topics currently taught in immunology courses and the degree to which they are time-prioritized by educators.

There is consensus in time prioritization-based ranking of which topics to include in an introductory immunology course and the general emphasis that each topic should receive. The topics identified in this report that had the greatest consensus (Adaptive Immune System, Innate Immune System, Host-Pathogen Interactions, and Molecular Mechanisms of Immunological Responses) were those that encompass several aspects of basic immunologic principles. The uniform emphasis on principles related to understanding the normal function of the immune system is not entirely surprising and likely reflects the fact that these topics constitute the foundation upon which students can begin to apply their understanding of the immune system to health and disease. Although these results likely reflect the perceived value of these content topics by the broader immunology educator community, it is also possible that they were chosen because of their broad applicability for various student cohorts—premedicine, pre-allied health professions and research-bound—or, alternatively, because textbooks have prioritized these topics. Importantly, the comprehensive nature of these four topics means that subtopics included by individual instructors could be quite variable, highlighting the need for in-depth analysis of the content covered in each of the four topics.

Equally important is the analysis of factors influencing the prioritization of topics taught in an immunology course. Institution type and student population had no effect on the emphasis placed on topics, suggesting that topics are being selected in courses at primarily undergraduate institutions versus institutions offering masters or doctorate degrees similarly, as well as at both the undergraduate and graduate levels. However, instructor bias is linked to those who currently teach and those who have long-term teaching experience. The Immunologist's Toolbox, Hypersensitivity Disorders, Tumor Immunology, and Evolutionary Aspects related to immunology were given greater emphasis by instructors currently teaching a course than those not currently teaching. Instructors with 10 or more years of teaching experience placed greater emphasis on Host–Pathogen Interactions, Mucosal Immunology, Transplantation, and Evolutionary Aspects of Immunology than instructors with fewer than 10 years of experience. Importantly, bias towards these topics did not supersede the emphasis placed on the Adaptive Immune System and Innate Immune System. These findings may reflect the fact that instructors adapt to include more advanced content or the application of foundational concepts based on their own familiarity with the subject, or based on their perception that more advanced, applied information significantly benefits the student population in a course.

Indeed, a limitation to this analytical methodology is that the survey did not ask about the length of the course being taught or specific course goals (targeted knowledge for specific student populations), or instructors’ areas of interest, which are among the important factors in selection of core topics for a course (30). Furthermore, emerging topics in immunology, such as Evolutionary Aspects related to immunology and Metabolic Demands of the Immune System, are among the least covered topics in courses taught by our pool of respondents. These findings may
FIGURE 5. (A) Mean ± SE rankings of importance of core competencies for student learning in the context of immunology on a scale from 1 (not at all important) to 5 (extremely important). Shared letters above bars indicate no significant difference ($p > 0.05$) by Student-Newman-Keuls post-hoc pairwise comparisons. (B) Breakdown of rankings by category. Categories (competencies) include: i) Ability to apply the process of science (Process); ii) Ability to communicate and collaborate with other disciplines (Comm & Collab); iii) Ability to understand the relationship between science and society (Sci & Society); iv) Ability to use quantitative reasoning (Quant Reason); and v) Ability to use modeling and simulation (Model & Sim). Sample sizes, $n=67–68$. 
reflect the prioritization of topics when constrained by time, but may also suggest that widespread knowledge of, or interest in, such niche or newly emerging topics by immunology educators is limited. It is also important to note that evolution and immunometabolism are not standard topic headings in common immunology textbooks, again reflecting the influence textbooks may have in directing course content or possibly highlighting a lack of instructor resources on these topics.

Bioscience graduates require several skills which can be broadly classified as transferrable skills and technical skills. A survey by Thompson et al. (2018) identified technical skills that are considered important for undergraduate life science programs (31). However, 47% of respondents identified that they did not have a lab associated with their immunology course. Several factors may influence an educator’s ability to have a lab component within an immunology course, including: 1) laboratory space available to set up and run an immunology lab; 2) other courses within the curriculum that may cover immunoassays or related techniques; 3) resources for cost-efficient immunology lab activities; and 4) undergraduate student access to immunology-focused research labs on campus. Although some technical laboratory skills that are taught in other laboratory classes can apply to immunological settings, such as cell culture or Western blotting, it is also important to teach these skills in the context of immunology, and to include immunology-centric techniques, such as flow cytometry and Enzyme-Linked ImmunoSorbant Assay (ELISA). It can be argued that immunology labs, if available to instructors, can provide an excellent platform to impart desirable skills and competencies, including transferrable skills through team work and collaboration on interdisciplinary projects.

An approach that focuses on conceptual, outcome-focused understanding and not just factual knowledge has been emphasized previously through national calls for action (13, 32). To address such a call, many educators and professional, discipline-specific societies have laid out course-design frameworks based on the backward-design or integrated-course design approach (33) that emphasize concepts over textbook content (34–36). The advantages of adopting such outcome-focused, student-centered approaches are numerous, including promoting equity in STEM education (37, 38). A study published last year, involving students from 20 institutions, demonstrated the importance of measuring student understanding of core concepts at various stages in a biology program to enhance student performance and highlighted the value of assessing core concepts not only at the course but also at the program level (14). Based upon Couch et al. (14), it is clear that identifying core concepts and evaluating student understanding of these concepts using appropriate tools, such as concept inventories or learning progressions, are key to identifying aspects of the course or program that need further development or improvement.

In conclusion, data from this study identify content, skills, and competencies that are time-prioritized and considered important, respectively, in undergraduate immunology education. This is an important first step in identifying current practices in the immunology classroom that will be informative for immunology educators in the development of resources such as a statement of fundamental concepts and concept inventories that have been integral in the educational practices of other science disciplines.

SUPPLEMENTAL MATERIALS

Appendix I: Survey tool

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