Special Feature

Standards for the Ph.D. Degree in Biochemistry and Molecular Biology

This article represents the recommendations of the Committee on Education of the International Union of Biochemistry (IUB) regarding standards for the Ph.D. degree in biochemistry and molecular biology. Comments, and similar submissions to the extent that they do not duplicate the present material, are invited regarding training for the Ph.D. degree in the other biological disciplines represented by FASEB.

Rationale

During the twentieth century the number of students being prepared to conduct research in biochemistry and molecular biology has grown, and the process has become a major industry, producing about 1000 Ph.D's per year. In the first several decades those few active investigators who were responsible for the growth of the field consisted of a brotherhood of individuals who were well informed about each other's activities and aware of the status of research throughout the biochemical world. Then, instruments and techniques were relatively simple, the rate of change in the field was slow, and the judgments of the established investigators about advancing their apprentices to independence were generally similar. However, as a result of explosive growth and fragmentation into subspecialties, the thousands of scientists qualified to supervise professional training in biochemistry and molecular biology now comprise a heterogeneous group, and the informal methods of the past no longer serve to maintain similar standards among nations or even among institutions within a country.

Biochemistry and the related disciplines that apply chemical and physical methods and principles to the solution of biological problems are among the most vigorous and productive areas of scientific development. Although a large number of investigators have continued to develop the intellectual and experimental aspects of these sciences, however, there is evidence that many holders of a Ph.D. degree are incapable of contributing to scientific progress or of applying science to practical problems. The profession must adapt to changes in itself and its environment to prevent deterioration. Although progress in scientific knowledge and understanding does not come equally from all members of the profession, most of society accepts that one Ph.D. is equivalent to another. Some established departments do not contribute significantly to the international literature but do award Ph.D. degrees. Differences in competence of individuals appointed as postdoctoral fellows or junior faculty members have been known to result in prejudice against individual departments or even against entire countries. The differences are great enough to indicate that the quality of the profession may be jeopardized if no action is taken to formulate and maintain standards.

Among the reasons for the differences in professional training is the diversity of educational systems in various countries that prepare students in very different ways to enter professional study. However, the end result should be the same, regardless of the methods used: a holder of a Ph.D. in Biochemistry should have the knowledge, skills, perspectives and understanding to be capable of independent scientific work of a quality satisfactory to others in the field.

Science depends on integrity. One of the functions of editors of scientific journals is the elimination of imprecise statements before publication, so that other investigators can repeat published experiments without difficulty. In general, little is accomplished in duplicating effort, and most research is based on the results obtained by others. Scientists often disagree about interpretations, but the accuracy of reporting methods and results of measurements is not questioned except in rare cases when aberrant behavior is suspected. Well-publicized examples of publications that contain false

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results are evidence of the effectiveness of the self-correcting mechanisms of the scientific system. But every instance of dishonesty, no matter how trivial, has the potential to harm individual scientists and the relationship between science and the rest of society. Because of this, students must be trained in an atmosphere of unquestioned integrity; any act of deliberate distortion or misrepresentation should be considered by the appropriate administration authorities as grounds for dismissal or for a severe warning with follow-up monitoring. It is assumed that every department or laboratory engaged in the pursuit of scientific knowledge has an atmosphere of mutual trust and that unethical behavior will occur so rarely that procedures designed specifically to detect it would be inappropriate.

As the fields of biochemistry and molecular biology develop even faster and as the potential for material rewards increases, competition for priority becomes keener. One danger is that this could lead to misrepresentation of data and the omission of reference to related or similar published work. Science remains, nevertheless, a collaborative effort, and graduate education must emphasize the interdependence of scientists on each other and the feeling of participation in the work of an international community of trustworthy scholars. Those who want to join this community must accept the ethical precepts that, historically, have characterized science.

The experiences that have brought illustrious investigators into the biochemical sciences have been so varied that it would be presumptuous to try to design a program of education that would be ideal for everyone. Further, in a field that is still evolving rapidly, scientists looking to the future must not be fettered by restrictions imposed by others. Therefore, this document does not prescribe procedures to be followed. Instead, it describes behavioral abilities that should characterize those awarded a Ph.D. degree, suggests how these abilities may be acquired as well as some methods by which progress toward attaining the abilities may be assessed, and proposes criteria for the overall evaluation of candidates for the degree. These guidelines are intended as an aid to university departments, to national organizations that set standards for graduate education, to those scientists who serve as external examiners to evaluate theses, and to candidates for graduate degrees.

Guidelines for the Ph.D. Degree in Biochemistry and Molecular Biology

The purpose of a Ph.D. program is to train independent, reliable, and competent research scientists. Although many holders of Ph.D. degrees find employment that does not involve research, having the degree implies that an individual is able to pursue a research problem to a meaningful conclusion. The research experience obtained in acquiring the Ph.D. degree should assure that the awardee understands and accepts the values of scientific research and is capable of using professional standards in all professional activities, i.e., teaching, practical applications or administration, as well as research.

Although biochemistry and molecular biology are experimental sciences, the Ph.D. candidate should not be trained as a technician. The training of every student should be sufficiently varied so as to give a theoretical understanding of the major techniques in current usage and should include enough practical experience to encourage the use of any methods that might contribute to the solution of problems. However, specialization of productive investigators and collaborations within research teams and between established scientists in different institutions are characteristic of present-day research. Therefore, students should not be overtrained in laboratory techniques not directly involved in their own research so that other essential skills are neglected.

Standards

1. The candidate should demonstrate a general knowledge of biochemistry and molecular biology and a detailed knowledge of the topics related to the area of research.

A candidate for the Ph.D. degree should go beyond the level of comprehension attained at the undergraduate level, where frequently the broad principles and terminology of the discipline based on recall of textbook information are sufficient to satisfy examination requirements. It should be at a professional level; i.e., based on an understanding of the experimental method(s) from which some of the basic principles of the science have been derived, rather than on the conclusions that others have drawn from the use of these methods. Thus, the student should read and analyze original publications in some areas as well as review-type papers published, for example, in Advances in Enzymology, Trends in Biochemical Sciences, BioEssays, Cell, Annual Reviews of Biochemistry, Nature, and Science. Such a knowledge of biochemistry and molecular biology implies familiarity with the structures and properties of common biomolecules, major metabolic pathways, principles of regulation of biological phenomena, the organization and function of subcellular structures and organelles, genetic expression, structure and replication, and the experimental basis for some of the current beliefs and models in the particular area of research. Professional knowledge should be attained by the time the candidate is awarded the Ph.D. degree. Because the extent to which such knowledge is acquired during undergraduate education varies, the supplementary education during the Ph.D. training period must be adjusted.

The attainment of appropriate insights can be evaluated formally (by essay writing, comprehensive oral tests, etc.) or informally (by questioning on matters relating to the research proposal, during periodic review of progress, during seminars or journal-club presentations made by the candidate, and during review of early drafts of the candidate's thesis). Although
evaluation is likely to be the supervisor's responsibility, it could also be shared by the candidate's supervisory committee and the supervisor.

2. The candidate should be familiar with the literature of biochemistry and molecular biology and should have the ability to keep abreast of major developments and acquire a working background in any area.

The scientific literature is the lifeblood of the growth and development of a discipline. It contains not only the results of investigations conducted by established scientists, but also their reasoning, experimental strategies, descriptions of technique and materials, discussion of results and evaluation of hypotheses, and the models of processes and phenomena that summarize much of the accumulated wisdom of the discipline. Familiarity with the literature identifies areas that have already been explored or that require exploration, and those where available results or interpretations are still controversial. The literature is the major link between biochemists throughout the world and is the repository of a vast amount of scientific information. This is the same literature to which candidates are being prepared to contribute during their training and in the future. The abilities to review the literature, to evaluate it critically, to abstract from it the useful and the valid as a basis for further exploration or investigation, are essential for an independent biochemist.

Avenues for developing and evaluating these abilities include: the preparation of the research proposal; seminar and journal-club type presentations; preparation of results for publication and periodic review of progress; preparation of the thesis; and preparation of a proposal for a research grant.

3. The candidate should possess technical skill in laboratory manipulation.

A doctoral candidate cannot acquire formal training in every available technology because the number of experimental techniques is so large. Rather, the candidate should be expected to have acquired enough technical skill to function in the research for which the degree is to be awarded. The candidate should demonstrate capability in the laboratory techniques related to the research project, a good understanding of the theoretical basis for these techniques, and sufficient self-confidence and competence in laboratory methodology so as not to be inhibited in adopting such new technology as may be required for carrying out research in the future. Technical competence and flexibility are essential tools for independent research.

Avenues for developing this ability include carrying out the experimentation for the thesis, specially designed laboratory courses, or short periods of training in other laboratories.

4. The candidate should demonstrate skill in the recognition of meaningful questions for investigation in biochemistry and molecular biology.

This ability arises in part from familiarity with and critical evaluation of the general literature of bio-

5. The candidate should demonstrate that oral and written communication skills have been acquired.

Scientific research has limited value until its results and their interpretation are made available to the scientific community. Scientists communicate by giving lectures and seminars, by posters, by periodic reports on their research, by applications for grant money, and by writing up material for publication. Communication skills are learned through practice and by acquiring confidence in latent abilities, and they need not be taught through formal courses during the doctoral process, but should form an integral part of the process. There are many opportunities during the doctoral process for their development, e.g., in the preparation of the research proposal, the periodic review of research progress, the preparation and oral defense of the thesis, preparation of research material for publication, and journal-club presentations and seminars. Opportunities should also be taken for discussion of ethical aspects in the presentation of results, and in the attribution of credit for the work of others, including appropriate reference to published work.

It is the responsibility of the supervisor or of the department or institute where the candidate is to work to indicate to the candidate at the beginning of the doctoral training what is expected and to provide positive feedback and guidance at every opportunity.
6. The candidate should demonstrate skill in designing experimental protocols and in conducting productive independent research.

This skill is of fundamental importance for an independent biochemist. Its acquisition is demonstrated by the successful completion of a self-initiated piece of research that leads to publication in an international refereed journal. This involves asking questions at an appropriate level (not too trivial, not too large), carrying out appropriate experiments with suitable controls, statistical treatment and analysis of the results, deriving of answers (i.e., conclusions) to the questions posed, and ultimate acceptance by the scientific community via a refereed publication.

This skill is not acquired simply by collecting or compiling data, by cataloguing observations, or by other activities in which the candidate serves as a technician. The candidate must participate actively in selecting the problem. Supervisors should assist in orienting their candidates to the relevant literature but should not impose their will on the students. The supervisor and the supervisory committee should periodically evaluate the progress in a critical way while allowing the student to carry out independently planned experiments and even to learn from mistakes (within reasonable limits set by budgetary and safety considerations).

The original description of the thesis problem should not be too restrictive. The candidate should be encouraged to recognize leads suggested by results and be permitted to change the problem if the change appears likely to produce more meaningful results. The balance between persistence in overcoming difficulties and wasting time on poor ideas must be learned by experience. Similarly, the lure of tempting new ideas must be resisted to the extent needed to bring projects to publishable conclusions.

Supervising student research requires subtle adjustments. In general, candidates begin with little relevant knowledge, restricted skills, and limited perspective and require considerable guidance. However, the naive beginner must eventually become an independent investigator during the thesis work. The development of skills and independence is acquired only through practice. The supervisor must decrease detailed directions as the project proceeds and may have to accept a loss in efficiency in the laboratory work as part of the cost of professional education.

The supervisor and the candidate thus become colleagues in a joint research project, but not as equals. Because the process of doctoral training contains a major element of apprenticeship, the supervisor is not only a teacher but also a major figure in determining the relationship of the candidate to the scientific community and of his subsequent professional opportunities.

Role of Formal Graduate Courses

Formal courses are a convenient route to acquiring information in a field of study and are frequently used to expand the general information base of students. Because the primary goal of graduate training is gaining independence and becoming familiar with the pertinent literature, formal courses are useful to the graduate program only if they allow the student to become competent in acquiring knowledge independently and if the acquisition of information is not used as the dominant measure of the student's development. Graduate-level courses should therefore facilitate the student's use of the literature and be concerned with the student's active self-education. Inasmuch as the independent scientist needs to keep up with developments in the field, any required graduate courses should be directed toward this future need.

Graduate courses in biochemistry and molecular biology should be designed to produce better scientists. They should be designed to develop permanent intellectual skills rather than the accumulation of transient, memory-based information, and should contribute to the development of a professional attitude. Regardless of course content or format, accumulation of credits by passing courses does not provide evidence that the candidate is better prepared to contribute to science.

Courses may be time-consuming and can disrupt experimental work, while the knowledge and skills that they may foster can be acquired in other ways (e.g., journal-club activities, reviews of the literature on selected topics, and seminars on topics unrelated to the research).

Role of Academics Other Than the Supervisor

Though the doctoral process is often viewed as being based largely on the supervisor-candidate relationship, the complete training of the candidate to meet these standards may be, and frequently is, beyond the ability of the supervisor. Few, if any, supervisors are completely self-sufficient, so other academics and doctoral candidates have an important role in a candidate's training. This not only broadens the scope of the learning environment for the candidate, but also demonstrates the social and interactive nature of scientific research.

It is the role of the department or institute in which the candidate is being trained to provide the environment in which the skills and competencies outlined in Section III can be acquired and to help identify others besides the supervisor who should participate in training the candidate.

Duration of Doctoral Training

The transition from student to professional does not proceed at the same rate for everyone. An even greater variable is the period for completion of various research projects. It is not reasonable to expect that the requirements for a Ph.D. degree can be completed within a short time. Sometimes outside forces (usually govern-
mental ones) apply economic pressures and limit the
time for graduate training. When this happens, mem-
bers of the profession should resist awarding degrees
prematurely or rejecting students who could become
useful professionals if they had longer periods of train-
ing. A Ph.D. degree should identify an individual who
has acquired high standards of scientific research and
who does not compromise those standards to meet ar-
bitrary deadlines.

Because the candidate is expected to acquire or de-
velop a professional philosophy and professional values
in addition to technical knowledge and skills, regardless
of success in research, the period of training should not
be less than 3 years.

The progress of every candidate should be monitored
by a supervisory committee. Decisions about abandon-
ing unproductive projects should not come suddenly
after several years of research, but should arise from
discussions with the candidate while there is still time
to complete the degree within the conventional period.
Serious questions must be asked early in the training
process about the abilities of the candidate to complete
the type of work that will lead to a satisfactory thesis
within a reasonable time, but arbitrary time limits
should be flexible.

The Doctoral Thesis

The doctoral thesis is the ultimate tool for evaluating
the acquisition of the skills and abilities required for
certifying a candidate as a competent, independent sci-
entist. It must serve not only to ascertain that the stu-
dent has participated in successful, meaningful re-
search but also that the student's contributions have
been significant.

The doctoral thesis may take different forms. It may
be a lengthy document that thoroughly reviews the
literature, explains the problem(s) selected, describes
the methods, provides a complete presentation of ex-
perimental results, and offers a long discussion of the
interpretation and implication of the findings. On the
other hand, it may be one or more published papers. As
it is not possible to evaluate the student's contribution
to any formal publications, especially when there are
other authors, and because journals restrict the amount
of explanatory and interpretive material, the thesis
should include material written by the candidate to
supply information beyond that included in published
papers. It should show clearly that the candidate has
put the research into scientific perspective and that the
student's contributions to the research are differen-
tiated from those of other contributors. Such material
should introduce each publication used as part of the
thesis, and there should also be a general discussion
that establishes the significance of the research and its
implications for future investigations or applications.

The size or volume of thesis material should not be
used as a criterion in its evaluation.

Previous publication of material to be included in a
thesis should be encouraged. The rapid pace of sci-
entific development requires that all meaningful research
be published as rapidly as possible. The Ph.D. degree
should be awarded only for a thesis that contains origi-
nal work already published or deemed suitable by the
examining body for publication in an established, refe-
reed journal in the field.

Concluding Remarks

Experience in various institutions and countries has
shown that competent biochemists can be produced by
diverse systems, ranging from the highly structured to
the almost completely unstructured. Because external
review is frequently needed, however, it is essential that
all departments or institutions in which training for the
doctoral degree is undertaken develop instruments for
evaluating the competence of their candidates and es-

cablish procedures for developing all of the professional

skills characteristic of successful investigators before the
Ph.D. is conferred.

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