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MiniReview

Biomedical PhD Education – An International Perspective

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Abstract: The PhD, otherwise known as the doctor of philosophy or Dr. Phil., is an internationally recognized degree, indicating that the PhD graduate has received training in research under supervision. Traditionally, the PhD was the route to an academic career, with most successful PhD graduates receiving tenured university positions. However, over the past 20–30 years, and particularly the past 10 years, the situation has changed dramatically. Governments in many countries have invested massively in PhD education, believing that trained researchers will contribute to the 'knowledge society', and thus increase the competitiveness of their countries in the future economies of the world. Thus, only a small fraction of PhD graduates now end up in academic research. Yet, the PhD remains a research degree, and indeed, institutions have become heavily dependent on PhD students for their research output. The situation has thus created a paradox. On the one hand, it has become essential for institutions to have many PhD students and for the research performed to be of the highest level. On the other hand, the careers of PhD students are not necessarily going to be directly related to the research performed during their PhD studies. The purpose of this article is to explore how this seeming paradox is being addressed in biomedicine and to show that far from being inconsistent that the two aspects are in fact complementary. The article is based on the author's experience as Head of Aarhus Graduate School of Health Sciences 2002–2011 and his work with graduate schools across Europe and internationally through the organization ORPHEUS.[1]

The PhD degree was first introduced at the Humboldt University in Berlin after its founding by Wilhelm von Humboldt in 1810. His vision was to strengthen the research by ensuring training for research under supervision, successful students being awarded the doctor of philosophy degree. The concept appears not to have received great support outside Germany, and indeed, it was first in the USA that other universities began to award a PhD degree, the first US PhD student being Arthur William Wright at Yale in 1862. The concept spread to Canada, where the first PhD degree was awarded in Toronto in 1900. Under pressure of hostilities during the First World War, the UK government encouraged the development of research training, and the first UK PhD was enrolled at Oxford in 1917. Since then, the PhD degree spreads steadily in Europe. In some countries, notably in Scandinavia, there was reluctance to introduce the PhD, because these countries already had a more advanced research degree given to established researchers. However, even there the PhD has been accepted, the PhD being officially introduced, for example, in Denmark in 1989. Also outside of Europe, the PhD has become widespread, with almost all developed countries now having PhD programmes [1–3].

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[1]Organisation for PhD Education in Biomedicine and Health Sciences in the European System.

In the early days, PhD students would typically enter their PhD programmes as a result of personal contact with a professor. Either professors would ask particularly promising undergraduates whether they would be interested in an academic career or students would ask particularly distinguished professors about the possibilities of working with them. The relationship was informal, the university only becoming involved when the student submitted his (or occasionally her) thesis. Later, at many universities, PhD students were registered, but otherwise it was often entirely up to the professor to supervise the student. The project was usually that of the professor, and in the absence of technicians, much of the work was mundane with PhD students doing routine laboratory work. Salary (if there was one) was low, but acceptable as the PhD programme was seen as a training leading to later academic employment. The training was unstructured, the PhD student being expected to pick up academic mores along the way. Probably, the student would attend academic conferences, might even make a presentation, but this was not obligatory. Likewise, results might be written up as an article, but this was thought usually to be something that was carried out after the thesis had been accepted. Indeed, the attitude was often that the student was not qualified to contribute to the scientific literature before receiving the PhD qualification. In due course, when the professor agreed that sufficient work had been carried out, the PhD student would write up the results of all the experiments in the classic PhD thesis, a monograph of 300–400 pages. The professor would then invite a colleague to examine the thesis, and the professor and colleague then held a

viva with the student, where the thesis was examined line by line. The student would also be expected to discuss in detail the methodology used. The result of the viva could be that the thesis was accepted, or that it was returned for revision, or that it was rejected. Theses returned for revision had to be rewritten and rebound, after which a new viva was held.

This traditional approach provided solid training in scientific method, hands-on understanding of methodology and critical analysis of the data. A PhD graduate was recognized as a trained researcher, a member of the academic community and qualified to contribute independently to scientific literature and scientific meetings.

New Times

As long as it was only some professors who occasionally had a PhD student, and as long as there was a modest increase in the number of academic positions, the system was sustainable: there was space in academia for the successful PhD students. In the past decades, however, the expectation has been that all professors should have several PhD students, and the number of PhD students worldwide has increased rapidly. In Europe, there has been a 50% increase over the past 10 years [4]. In the USA, there has been a doubling in biomedical PhDs over the past two decades [5]. In some countries, such as Denmark, the rate has been even greater with more than a doubling over 10 years. In China, the number of PhD students increased almost four times between 1999 and 2007 [6]. Clearly, with the number of available university positions stagnant or falling, the PhD is no longer an assured route to an academic career. Thus, for example, in the UK, according to a Royal Society 2010 report [7], around 50% of PhD graduates go immediately to non-research positions outside of academia, 30% to postdoctoral positions and around 17% to non-university research positions. Of those who move to postdoctoral positions, only around 4% find permanent academic research posts, the majority of the remainder going to non-research positions. Thus, only about 25% of PhD graduates use their talents in research activities (fig. 1). Similarly, in Norway, it was found that in 2009 of all Norwegians who received a PhD between 1970 and 2009, only 18% had a research position [8]. A report in Nature showed similar figures across the world [9]. On the other hand, a survey covering most of the member states of the European Union (EU), of EFTA as well as some of the most important other members of the OECD, such as the United States and Australia indicated that around 50% of PhD graduates are in research positions [10]. Some of the discrepancies may be due to the definition of 'research positions'. However, overall the data suggest that only a minority of PhD graduates find employment in conventional research positions and, with the current enrolment rates, even fewer are likely to do so in the future.

Focus on PhD Education

In Europe, the impetus for the current increased focus on PhD education came from a meeting of the European Union's Council of Ministers in December 2003, where it was decided

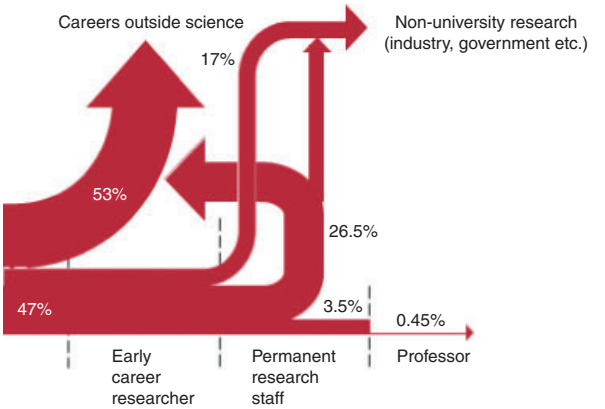

Fig. 1. Careers in and outside science in the UK. The diagram illustrates the transition points in typical academic scientific careers after a PhD and shows the flow of scientifically trained people into other sectors. It is a simplified snapshot based on recent data from Higher Education Funding Council for England [33], the Research Base Funders Forum [34] and from the Higher Education Statistics Agency's annual Destinations of Leavers from Higher Education (DLHE) survey. It also draws on Vitae's analysis of the DLHE survey [35]. It does not show career breaks or moves back into academic science from other sectors. Figure based on Figure 1.6 in *The Scientific Century* securing our future prosperity, 2010 Report of the Royal Society, London, 2010. Reproduced with permission from the Royal Society.

to extend the Bologna process from two cycles (bachelor and master's) to include a third doctoral cycle. The ministers emphasized 'the importance of research and research training … in enhancing the competitiveness of European higher education', and the need for PhD graduates to build the 'knowledge society'. As doctoral training was seen as synonymous with PhD education, the European Universities Association (EUA) had concerns that the new focus on doctoral training could lead to a reduction in the standard of the PhD. At a EUA conference held in Salzburg 2005, it was emphasized as the first of ten points that 'The core component of the third cycle is the advancement of knowledge through original research'. This makes the third cycle unique and different from the first and second cycles [11]. In other words, institutions that were capable of teaching the first and second cycles could not provide the third cycle unless they had a strong research environment, or else interacted with other institutions where such an environment was present. Among other points, the conference document from the 2005 Salzburg meeting also emphasized the importance of having structured PhD programmes, with competent supervision and assessment [11]. To emphasize the importance attached to doctoral education, the EUA set up a Council for Doctoral Education (EUA-CDE), which in a second 2010 Salzburg ('Salzburg II') document [12] provided more details about how the ten points could best be achieved.

In many countries, these initiatives were followed by increased financial support for PhD education, for example, in Denmark with government support for more PhD stipends and for the establishment of structured PhD education. Similarly, in other countries, the value of PhD students in increasing the research output was also recognized with most professors

taking on several PhD students at a time. Although firm data are not available, it is now thought that up to half the research output of biomedical institutions is performed by PhD students. Cutting enrolment of PhD students to a level consistent with the number of academic positions available is therefore not seen as an option. Instead, there has to be focus on ensuring that PhD programmes provide PhD students with competencies that they will need outside of academia. Nevertheless, in many institutions in many countries, the traditional apprenticeship model for PhD training still applies.

Criticism of the PhD

Perhaps because of the continuation of traditional approaches in some institutions, PhD training has in the past two years received substantial criticism in leading journals. The Economist [13] suggested that doing a PhD was often a 'waste of time' and that 'dissatisfaction' among PhD students was widespread. This view was opposed, but a few months later, Nature had a tranche of articles outlining current problems with PhD training [9,14–17]. It was, for example, intimated by a distinguished US author that 'Most doctoral programmes conform to a model defined in the middle age' [14]. The criticism has continued in 2012 [18]. To a large extent, the criticism has been directed at the more traditional forms of PhD programmes. However, such criticism raises doubts about all PhD programmes. Clearly, if the PhD is to maintain its historical reputation as a degree of excellence and if PhD training is to remain attractive to the brightest and best, some action is needed. As suggested recently, it should be ensured that PhD students remain a mainstay of current scientific research, the source of our future scientists, and a basis for providing persons with the skills needed to build knowledge societies [19].

The 'Modern PhD'

To deal with this criticism, graduate schools are changing the emphasis of their PhD programmes such that PhD students become managers of their projects, not technicians [12,20]. This can be carried out by ensuring that PhD students at an early stage of the programme have full responsibility for their projects from hypothesis generation to presentation of the results. PhD students thus need to be provided with skills that will allow them to set up protocols, ensure these are carried out, manage their project according to time-lines, obtain financing, establish networks, interpret and publish the results and present the results to scientific and non-scientific audiences, nationally and internationally. Some suggestions for the content of such a 'Modern PhD' are shown in table 1. Doing all this within the framework of a 3–4 year PhD programme is not easy. However, by viewing PhD students as managers of a project team, who are able to enlist the expert assistance of other colleagues and technicians, the traditional scientific level of a PhD thesis can be obtained. That PhD students should not themselves necessarily do all the work presented in their thesis was previously considered anathema, but one needs to consider whether such requirements for a 'Modern PhD' do not make this unavoidable [21].

In this process, the role of supervision is crucial, where it should be recognized that successful supervision is a two-way process, with responsibilities on both sides. In many graduate schools, formal contracts are made between supervisor and PhD student upon enrolment. These developments underscore the need for qualified supervision with relevant courses for supervisors, and also students [22].

Recently, the European Commission published a short document outlining the 'Principles of innovative doctoral training' [23]. This emphasized the need for research excellence as the basis for all doctoral training and the need for interdisciplinarity. It indicated that PhD students should have career development opportunities through being exposed to industry and other relevant employment sectors during their training. International networking was also advocated. Importantly, PhD programmes should also include training in generic (transferable) skills. The overall aim of the document was to describe the conditions that can ensure that PhD education makes a valuable contribution to the European knowledge society that will be able to compete with other economies of the future.

The Commission's document indicates that excellence in research must remain the *sine qua non* of a PhD programme

Table 1.

Some suggestions for the 'Modern PhD'.

PhD programmes should be performed in a strong research environment.
PhD programmes should train for both academic and non-academic employment.
Admission to a PhD programme requires a level corresponding to a bachelor and 2-year research-based master's. For countries not following Bologna, corresponding research experience should be obtained by other means.
PhD programmes should be structured and based primarily on a 3–4 year hands-on, original research project.
PhD programmes should include project-related course work covering about 6 months, including courses on ethics and transferable skills.
PhD students should have qualified and regular supervision.
There should be arrangements to allow PhD students to have time at another laboratory.
A PhD thesis should demonstrate an intellectual ability to be expected from completion of a 3–4 year research project at international level. This level is assessed as being a research output corresponding to the equivalent of three papers/manuscripts in international journals.
The PhD thesis should be evaluated by an assessment committee consisting of active scientists, who should be independent of the student and the supervisor, and preferably international.
The PhD defence should include a public lecture and examination. The examination can be in the form of closed viva.
PhD students should interact with the leadership of the graduate school regarding the management of PhD programmes.

This list is based on some of the standards listed in the ORPHEUS/AMSE/WFME PhD standards document, Aarhus University Press, 2012 [24].

and a firm basis of the institution's research basis. But a new attitude to the PhD is indicated, away from the idea that it consists only of learning scientific method and laboratory techniques towards having responsibility for a project. The quality of the research in such a 'Modern PhD' [21] should in no way be compromised by the other components of such programmes. Rather these, other components should enhance the quality of the research and the motivation of the students.

Quality Assurance

Most countries have more or less detailed regulations and guidelines for their PhD programmes and most emphasize the need for quality assurance. The European Commission's 'Principles of innovative doctoral training' referred to above [23] also emphasizes that quality assurance procedures are essential to ensure that the principles enunciated in the document are implemented. Similar comments are found in the EUA-CDE Salzburg II document [12]. Such procedures can either become very detailed if all regulations are to be fulfilled or else diffuse if the intention is only to determine agreement with the overall principles. In the field of biomedicine and health sciences, the present author has worked within the organization ORPHEUS (Organization for PhD education in biomedicine and health sciences in the European system) to develop a practical basis for such quality assurance. Here, the intention has been to define the essence of PhD education across Europe in a set of standards for PhD education all of which can be readily tested. This work, conducted as a collaboration between ORPHEUS, Association of Medical Schools in Europe (AMSE) and World Federation for Medical Education (WFME), has recently culminated in the publication of a *PhD standards document* entitled 'Standards for PhD education in biomedicine and health sciences in Europe' [24]. The brief document has eight one-page sections covering research environment, outcome, admission policy and criteria, PhD education programme, supervision, PhD thesis, assessment and institutional structure. Each section is divided into basic standards (items that must be fulfilled) and quality development (items indicating good practice) and annotations (explanations, recommendations and indications of flexibility). The recommendations for a 'Modern PhD' shown in table 1 are taken from this document.

Alternative Approaches

While many institutions and supervisors have embraced the concepts of the 'Modern PhD', the approval is far from universal. Many institutions, particularly in the UK and those countries worldwide which have historically been associated with the UK, are more prone to insist on the PhD providing rigorous evidence of individual scientific excellence and ability to conduct laboratory experiments, and to document, analyse and interpret these [25,26]. Less emphasis is based on dissemination and development of generic skills. Any course activity is optional. The important thing is for the PhD graduate to be a competent practical researcher. Other competencies can be developed afterwards, as can publication and scientific presentations. Such views are also held by many supervisors in institutions that officially espouse the 'Modern PhD' programmes as described above. These supervisors hold that one should not compromise on the traditional form of PhD training with its emphasis on individual scientific excellence. Provocatively, PhD students should 'spend their time in the laboratory'. Such concerns are understandable. But in the view of the author, they do not take account of the new demographics of PhD training where, as indicated above, only few PhD graduates will find academic research positions. While 3–4 years of work in the laboratory addressing a scientific question undoubtedly provides the PhD students with a number of competences, potential employers outside of academia are typically looking for additional skills. This indeed is increasingly recognized by institutions with more traditional PhD programmes, and from many discussions the present author has had with colleagues at different graduate schools in Europe and worldwide, the need to provide PhD students with generic skills is becoming more accepted. For example, Monash University in Australia has recently introduced the 'new Monash PhD' [27]. Fortunately, for the less convinced supervisors, experience shows that provision of structured PhD education that gives PhD students not only research proficiencies, but also generic skills, improves the research performance and allows PhD programmes to be completed on time.

An important condition for success of these new approaches to PhD education, with emphasis both on generic skills and the ability to complete within 3–4 years, is that PhD students need to have research experience before enrolment. Apart from the laboratory skills that they will have acquired, this allows them to develop – together with their supervisor – their own research project such that they are up and running from the first day of their PhD programme. Such research experience is built into the European undergraduate programmes that follow the Bologna process, where the master's programme will normally include a one-year research project [28]. In other countries, such as the UK, previous research experience is increasingly required for enrolment in PhD programmes [25]. In the US, potential PhD students have a two-year period of study corresponding to a European master's, during which they identify where they wish to do their PhD project, and to develop the project protocol [29]. In general, the new approach envisages that the time from admission to a bachelor programme to the completion of a PhD is of the order of 7–9 years. A time which is still more often exceeded than not.

Outcome

Given that there have been 200 years of autonomous development of PhD programmes in universities throughout the world, it is not surprising that there is substantial diversity in their content. Complete agreement about the detailed content of PhD programmes is thus neither practicable nor desirable. More agreement can be obtained about the expected outcome of PhD education. Here, opinion leaders are in no doubt that PhD education must be both a research degree and must

prepare for employment within or outside of academia. For example, the UK Quality Assurance Agency has written [25]:

> The importance of acquiring research and other skills during research degree programmes is recognised by research students, academic staff, sponsoring organisations, employers and doctoral graduates. These skills improve the research student's ability to complete the research programme successfully. The development and application of such skills is a significant element in the research graduate's capability for sustaining learning throughout his or her career, whether in an academic role or in other employment. Research students are encouraged to take ownership and responsibility for their own learning, during and after their programme of study, and to recognise the value of developing transferable skills.

As another example ORPHEUS has indicated [24]:

> First that the PhD programme leading to the PhD degree must provide students with competences that enable them to become a qualified researcher; that is a scientist able to conduct responsible, independent research, according to principles of good research practice. Second that completion of a PhD programme must also be of potential benefit for those who end in careers outside of academic or clinical research, by use of competences achieved during the PhD programme, including solution of complex problems by critical analysis and evaluation, appropriate transfer of new technology and synthesis of new ideas.

The challenge for the future is to ensure that these concepts are accepted not only by heads of graduate schools but also by the supervisors who have the responsibility for guiding their PhD students.

The demonstration that a PhD programme has involved 3–4 years of research at international level is normally assessed on the basis of the PhD thesis. Increasingly, the classic monograph is being replaced by a review and a number of papers, where ORPHEUS has recommended (table 1) that the level in biomedicine should be 'equivalent' to three first-author published papers (either published or manuscripts that the assessment committee find to be publishable). Fewer papers would be acceptable if published in high-ranking journals. The key word is 'equivalent' and, under all circumstances, it is the independent assessment committee which makes the scientific judgement as to whether the thesis is acceptable. The manner in which the PhD thesis is defended varies. Traditionally, the thesis is defended at a closed viva, where the examiners and the student sit at a table and go through the thesis in detail. In Continental Europe (taken here to include Scandinavia), the assessment committee normally makes a written evaluation of the thesis, often returning this for revision. When accepted, there is a public defence, where the student makes a presentation and is then examined. This procedure has the advantage that the student is tested in the ability to make a public lecture, but the importance of the oral defence in the assessment of the thesis varies widely between countries. In some cases, the defence is a real examination, but in others, it is more a formality. The present author suggests that there is here basis for a thorough discussion of the best manner to determine whether the PhD student has achieved the research excellence expected of a PhD programme, both procedures having their merits.

Further outcome is shown in table 2. The outcome listed will be of use both within and outside of academia. It has been suggested that the final PhD diploma should indicate the competencies achieved and the activities performed during the PhD programme, perhaps in the form of a portfolio (table 3) [30] or diploma supplement. Indeed, it could be considered whether such achieved competences should be assessed together with the PhD thesis when considering whether a PhD student should receive a PhD degree.

Postdoctoral Training

One response to the difficulty that PhD students have in finding academic employment on completion of their PhD programmes is to call for a greater number of postdoctoral positions. The idea is attractive, for the current system results in PhD graduates not being able to use the considerable expertise in their field which they have built up during their studies.

Table 2.

Expected outcome of a PhD programme.

The PhD programme leading to the PhD degree provides students with competences that enable them to become a qualified researcher; that is a scientist able to conduct responsible, independent research, according to principles of good research practice
Completion of a PhD programme is of potential benefit for those who end in careers outside of academic or clinical research, by use of competences achieved during the PhD programme, including solution of complex problems by critical analysis and evaluation, appropriate transfer of new technology and synthesis of new ideas.
Other *competences* relevant for PhD programmes would include that PhD students:
have demonstrated a systematic understanding of a field of study and mastery of the skills and methods of research associated with that field;
have demonstrated the ability to conceive, design, implement and adapt a substantial process of original research with scholarly integrity at a level that merits international refereed publication;
can communicate with their peers, the wider scholarly community and with society in general about their areas of expertise;
can be expected to be able to promote, within academic and professional contexts, technological, social or cultural advancement in a knowledge-based society.
Further competencies include leadership, ability to supervise work of others, project management and ability to teach.
The PhD qualification corresponds to level 8 in the European Qualifications Framework.

This list is based on Section 2 of the ORPHEUS/AMSE/WFME PhD standards document, Aarhus University Press, 2012 [24].

Table 3.
Suggested topics for a portfolio that PhD students should prepare at the conclusion of their PhD programme.

PhD thesis
Hypothesis development
Protocol development
Methodology
Project execution (probably with the help of others in the PhD student's team)
Interpretation of results
Presentation
Articles, reviews, abstracts
International conferences: participation, posters, lectures
Local meetings, department, national
Lay lectures
Patents
Courses, project-related, transferable skills
Team management
Grants received
Time in other laboratories, time abroad, time in industry or job placement
Networks established
Teaching

This list is based in part on discussions between Aarhus University and Edinburgh University, September 2012 [30].

However, it should be recognized that this only shifts the problem for the PhD graduates: most of them will, nevertheless, have to leave academia having spent even more years, when it may be even more difficult to obtain employment. A case could perhaps be made for converting some of the PhD stipends to postdoc stipends. If so, the present author would recommend that the postdoctoral students should continue to be provided with training in a variety of competencies needed outside of academia, as described above for PhD students. Such postdocs should be viewed as the very best students, and it should be ensured that they have the possibility to make even greater contributions to the knowledge society than PhD graduates. Under all circumstances, whether PhD graduates leave academia immediately after graduation or after a period as postdoc, they should take heed of the recent statement from NIH Director Francis Collins: 'I worry that a number of them are receiving the message that if they don't get a tenure-track position, they have failed. The good news is that nearly all postdocs are likely to be employed in interesting positions, but many will not travel a narrow academic path' [31].

The Need for Transparency

If top-quality students are not to be discouraged from entering PhD programmes, potential PhD students should be aware that successful conclusion of the programmes offered have a high probability of leading to demanding jobs either within or outside academia (table 4). This indeed is the case, because unemployment among PhD graduates is low (2% according to Eurostat [9]), and most PhD graduates find their employment to be stimulating and that their PhD education has been relevant. Thus, there should be full transparency about job opportunities for PhD graduates with information being provided before starting the programmes about the type of jobs obtained by those with PhD degrees. Career advice from supervisors should be a continuing part of PhD programmes, with institutional support being provided.

Table 4.
Some career opportunities for biomedical and medical PhD graduates.

Directly related to research
Academic research
Clinical research
Industrial research
Contract research organization
Research management
Other opportunities
Clinical positions
Higher education teaching
Funding organizations
Scientific writing
Scientific consultant
In vitro diagnostics, specialist laboratories
Evidence-based policy making
Own spin-off business
Marketing, sales, customer support, technical support,
Communications (internal, external), regulatory, quality control, quality assurance
Patents
Investment banking
Human resources
Administration

This list is based on the outcome of a workshop held at the University of Cologne, 27–28 November 2012: Career Development for PhD Students: Research Training for the Knowledge Society. http://www.zmmk.uni-koeln.de/content/orpheus_workshop.

Conclusion

As indicated above, the changed demographics of PhD training and the subsequent employment of PhD graduates has put pressure on the traditional form of PhD programmes. While the traditional emphasis on individual scientific excellence is to be highly respected, such training is in general less appropriate as training for the non-academic employment market, where most PhD graduates will use their talents. Thus, it seems imperative that PhD programmes include practical training in a range of generic skills. It is, however, also essential that such training does not prevent the research component of PhD programmes being at the highest level. These two requirements may seem mutually exclusive, but in fact, if PhD programmes are structured, with clearly defined PhD projects from the start, then both requirements can be achieved. Moreover, the generic skills developed enable PhD students to perform their research more effectively and better, particularly if PhD students are seen as project managers where they are able to enlist assistance for their project from other colleagues and technicians [32]. This at least has been the experience of the present author at his own institution and at other institutions where programmes closely following the concepts of the 'Modern PhD' [21] have research outputs at least as good as those from traditional PhD programmes, while also allowing students to obtain the full range of competencies described in table 2.

References

1 Powell S, Green H. (eds). The Doctorate Worldwide. Open University Press, Maidenhead, 2007.
2 Nerad M, Heggelund M. (eds). Toward a Global PhD. Univ Washington Press, Seattle and London, 2008.
3 Taylor S. The Post-Humboldtian Doctorate. In: King V, Deepwell F, Clouder L, Broughan C (eds). Academic Futures: Inquiries into Higher Education & Pedagogy. Cambridge Scholars Publishing, Cambridge, 2009;61–79.
4 European Commission. Innovation Union Competitiveness Report. 2011, Table I.4.2, http://ec.europa.eu/research/innovation-union/index_en.cfm?section=competitiveness-report&year=2011 (last accessed on 21 January 2013).
5 National Institutes of Health(USA). Biomedical Research Workforce Working Group Report. 2012. pp 1-156. http://acd.od.nih.gov/bmw_report.pdf (last accessed on 21 January 2013).
6 Wu B, Zheng Y. Expansion of Higher Education in China: Challenges and implications. China Policy Institute, University of Nottingham, Nottingham. 2008. Table 1. https://asab.nottingham.ac.uk/cpi/documents/briefings/briefing-36-china-higher-education-expansion.pdf
7 Royal Society, UK. The scientific century: securing our future prosperity. 1-76. 2010. http://royalsociety.org/policy/publications/2010/scientific-century/ (last accessed on 21 January 2013).
8 Thune T, Kyvik S, Sörlin S, Olsen TB, Vabø A, Tømte C. PhD Education in a Knowledge Society. Nordic Institute for Studies in Innovation, Oslo, 2012. ISBN 978-82-7218-846-6.
9 Cyranoski D, Gilbert N, Ledford H, Nayar A, Yahia M. The PhD factory. Nature 2011;**472**:276–9.
10 Eurostat, European Commission. Careers of doctorate holders. 2012. http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Careers_of_doctorate_holders#Employment_characteristics_and_work_perception (last accessed on 21 January 2013).
11 Christensen KK. Bologna seminar. Doctoral Programmes for the European Knowledge Society, 3-5 February 2005. European Universities Association, Salzburg, 2005. www.eua.be.
12 European Universities Association. Salzburg II Recommendations. 2010. pp 1-8. www.eua,be
13 Anonymous. The disposable academic. Economist 2010;**397**:156.
14 Taylor MC. Reform the PhD system or close it down. Nature 2011;**472**:261.
15 Editorial. Fix the PhD. Nature 2011;**472**:259–60.
16 McCook A. Rethinking PhDs. Nature 2011;**472**:281–2.
17 Fiske P. What is a PhD really worth? Nature 2011;**472**:381.
18 Wadman M. A workforce out of balance. Nature 2012;**486**:304.
19 Mulvany MJ, Lackovic Z. Modernizing the PhD: a need for standards. Intern Innov 2012;December:115–7.
20 Seeliger JC. Scientists must be taught to manage. Nature 2012;**483**:511.
21 Mulvany MJ, Lackovic Z. The modern PhD. Pharmacol Mat 2012;**5**:26–7.
22 Wichmann-Hansen G, Wogensen L, Eika B, Mulvany MJ. Successful PhD supervision – a two-way process. In: Castanho MARB, Güner-Akdogan G (eds). The Researching, Teaching, and Learning Triangle. 10. 1st Edition udg. Springer Publishing Company, New York. 2012;55–66.
23 European Commission. Principles for Innovative Doctoral Training. 2011. pp 1–2. http://ec.europa.eu/euraxess/pdf/research_policies/Principles_for_Innovative_Doctoral_Training.pdf (last accessed on 21 January 2013).
24 Mulvany MJ, Deckert J, Gordon D, Karle H, Lackovic Z, Lindgren S *et al.* Standards for PhD Education in Biomedicine and Health Sciences in Europe. 2012. For ORPHEUS, Association for Medical Schools in Europe (AMSE), World Federation for Medical Education (WFME). 2012. Aarhus University Press, Aarhus, Denmark. ISBN 978 87 7934 600 0. www.orpheus-med.org (last accessed on 21 January 2013).
25 UK Quality Code for Higher Education. Part B: Assuring and enhancing academic quality. Chapter B11: Research degrees. 2012. Quality Assurance Agency for Higher Education. ISBN 978 1 84979 550 0
26 Mulvany MJ, Goulding N. Safeguarding the PhD. Pharmacol Mat 2011;**4**:7–8.
27 The new Monash PhD. 2013. Monash University. http://www.monash.edu.au/migr/why-monash/phd/ (last accessed on 22 January 2013).
28 Bologna Process: framework of qualifications of the European Higher Education Area. www.bologna-bergen2005.no/EN/BASIC/050520_Framework_qualifications.pdf (last accessed on 21 January 2013).
29 National Institutes of Health. Biomedical Research Workforce Working Group Report. 2012.
30 Communiqué High Level Dialogue on Excellence in European Doctoral Training, Aarhus University, Edinburgh University, Aarhus, September 2012. www.au.dk (last accessed on 21 January 2013).
31 Collins F. Question and answer. Nature 2013;**493**:443–4.
32 Mulvany MJ, Lackovic Z, Jonsson R. PhDs Should be Managers, Not Technicians. University World News, 239, 2012;239.
33 Higher Education Funding Council for England. Staff employed at HEFCE funded HEIs. Trends, profiles and projections. Higher Education Funding Council for England, Swindon, 2005.
34 Research Base Funders Forum. First Annual Report on Research Staff Covering the Period 2003/04 to 2006/07. Department for Innovation, Universities and Skills, London, 2008.
35 Vitae. What Do Researchers Do? First Destinations of Doctoral Graduates by Subject. Vitae, Cambridge, 2009.