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A review and critique of academic lab safety research

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Over the past ten years, there have been several high-profile accidents in academic laboratories around the world, resulting in significant injuries and fatalities. The aftermath of these incidents is often characterized by calls for reflection and re-examination of the academic discipline's approach to safety research and policy. However, the study of academic lab safety is still underdeveloped and necessary data about changes in safety attitudes and behaviours has not been gathered. This Review article critically examines the state of academic chemical safety research from a multifactorial stance, including research on the occurrence of lab accidents, contributors to lab accidents, the state of safety training research and the cultural barriers to conducting safety research and implementing safer lab practices. The Review concludes by delineating research questions that must be addressed to minimize future serious academic laboratory incidents as well as stressing the need for committed leadership from our research institutions.

On December 29, 2008, Ms Sheharbano Sangji, a research assistant in the lab of Dr Patrick Harran at UCLA, was working with a large quantity of *tert*-butyllithium when the pyrophoric chemical spilled and ignited her clothing, leading to 2nd and 3rd degree burns over 40% of her body. The 23-year-old died in hospital three weeks later. The California OSHA report[1] into the death of Ms. Sangji is provided in the Supplementary Information.

Contributing factors to this accident can be identified at multiple levels: the individual, the laboratory, the department, the institution and the discipline itself[1]. At the time of the accident, Sangji was not wearing a lab coat[1] and was not following the manufacturer's safety protocols for handling large quantities of a pyrophoric chemical (for example, the reagent bottle was not clamped and a plastic syringe was used instead of glass)[2]. Despite knowing that she had limited experience working independently in chemistry labs, Harran, her supervisor, stated that he had not trained Sangji in the proper handling of pyrophorics and that the necessary technical guidelines were not readily available in the lab[1]. A post-doctoral researcher in the Harran group who recalled that he may have offered general guidance to Sangji about the transfer and handling of *tert*-butyllithium acknowledged that he did not follow the manufacturer's safety instructions for handling this reagent and did not believe he had ever read them[1,3].

It is not clear that a lab coat was actually ordered for Sangji by Harran or anyone else at UCLA[1]. In fact, use of personal protective equipment (PPE) was not officially mandated by university policy[1]. Pending completion of renovations to laboratory space on another floor, Harran had been given temporary space that was 30–40% smaller than his requirements and did not have a stockroom for storing chemicals[1]. In the 14 months prior to Sangji's death, UCLA had failed to report to the California Division of Occupational Health and Safety two other similar, non-fatal, incidents from other research groups involving burns and facial lacerations to students not wearing appropriate PPE[1,4,5]. Although experienced researchers will criticize the technique employed for the pyrophoric chemical, an individual who has not been trained in their use cannot be faulted: in virtually all published research where *tert*-butyllithium is used, the hazards of working with this chemical are rarely spelled out[6].

In 2012, Dr Neal Langerman, former chair of the Division of Chemical Health and Safety of the American Chemical Society (ACS), described the UCLA incident as, "The most serious challenge to the practice of laboratory safety in many years. The lessons learned should result in fundamental cultural changes in the approach to research safety"[7]. Yet despite the occurrence of this tragedy and other serious high-profile incidents in the intervening years (for example, the death of Michele Dufault at Yale University, and explosions causing significant injuries to Preston Brown at Texas Tech and Dr Thea Ekins-Coward at the University of Hawaii)[8–11], the field of academic lab safety has received little empirical attention, and research efforts in this area have been fragmentary[12].

In many cases, questionable research methodologies seriously undermine the reliability, validity and applicability of findings. As a result, policies and procedures around safety are developed in a reactionary, ad hoc patchwork rather than on a solid, comprehensive, empirical foundation[13]. More than ten years on from Sangji's death, we can conclude that there is no evidence of sweeping, fundamental changes, nor of major paradigm shifts in how academic lab safety is approached within the discipline. As this was a high-profile case, and was initially expected to be a turning point for academic lab safety, we will return to this example for illustrative purposes. However, we want to emphasize that safety is not a problem unique to the Harran laboratory or to UCLA: the failures that led to the death of Sangji are systemic and could have occurred in many research groups at many institutions. The problem is, and sadly remains, much bigger than any single case[14].

This Review aims to critically examine the current state of chemistry laboratory safety research, to discuss the barriers to conducting and implementing results of this research, and to call for a re-examination of, and a commitment to, academic chemistry's role in accident research and prevention.

Type and frequency of accidents in the academic setting

All practicing chemists in academic institutions are aware of and acknowledge that lab accidents and near-misses (for example, fires, leaks, glassware implosions or explosions, spills, equipment or

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instrument misuse resulting in equipment failure that do not result in injury) occur regularly[15,16]. However, to the best of our knowledge, no researcher, university, regulatory body or professional organization has collated the annual incidence of academic laboratory accidents. No comprehensive dataset is currently available on the type or frequency of accidents or near-misses in academic laboratories[5,17]. Although several researchers have attempted to create accident databases[15], participation in these initiatives is voluntary, meaning that these sources are incomplete and inadequate for the purposes of research and comprehensive policy development. This lack of data severely hampers any efforts to understand accidents, to take steps to prevent them, to reduce their frequency and severity or to create evidence-based safety guidelines.

It could be expected that gathering, collating and analysing lab accident data in order to determine prevalence rate might fall under the purview of governmental regulatory agencies. However, to our knowledge, neither the Occupational Safety and Health Administration (OSHA) in the United States nor any of the 13 provincial and territorial safety boards in Canada, despite receiving accident reports and carrying out investigations, has ever compiled or analysed this data as a whole. In addition, OSHA regulations do not apply to all universities or to all lab personnel working in a university, depending on their employment status. Since 2001, the US Chemical Safety and Hazard Investigation Board (CSB) has reported 120 academic research laboratory accidents resulting in 87 evacuations, 96 serious injuries and three deaths (Table 1)[18]. However, these represent only those accidents that universities have been required to report due to the severity of the consequences. Regulators may thus remain unaware of potentially major incidents or significant near-misses if no one was seriously injured[19].

There has been very little academic research into the prevalence and incidence of laboratory accidents. In the only study we could find using a proper multi-institutional epidemiological approach, Hellman, Savage and Keefe, examining 574 accidents occurring at 13 Colorado institutions between 1966 and 1984, found that 81% of accidents occurred in teaching labs, 13% in research labs and 2% in fabrication rooms[20]. Most accidents occurred in entry-level chemistry lab courses or organic lab courses, and most commonly occurred among younger individuals[20].

There have been a few, mostly small, studies focused specifically on the prevalence of research lab-related injuries. In one survey from *Nature* and UCLA of 2,400 scientists, 30% reported having witnessed a lab injury severe enough to warrant attention from a medical professional[21]. A small pilot study of 56 lab personnel in Canadian chemistry and biology labs revealed that 15% of those surveyed had sustained at least one injury[22]. Simmons, Matos and Simpson found that lab accidents, both in teaching and research labs, represented 18.4% of the total incidents reported at Iowa State university from 2001 to 2014, and that student employees were the victims in one third of injury reports[23].

Aside from the study by Hellman and colleagues, there have been few studies of injuries sustained in undergraduate teaching laboratories, perhaps because these situations are more carefully controlled and involve less dangerous reagents. However, one study of students enrolled in general chemistry and organic chemistry courses found that 12% sustained an injury, the most common ones being chemical burns, inhalation of irritating or toxic gases and cuts[24].

Although this research is incomplete, it certainly paints a troubling picture. One major issue is that research into laboratory injuries tells us nothing about the overall accident prevalence rate. 'Close calls' involving no injuries are anecdotally far more common than accidents involving injuries, but are rarely even reported unless the property damage is severe. In addition, the true accident prevalence rate is likely worse than these results suggest as there is some evidence to suggest that underreporting is a significant problem in science. Studies conducted in this area have shown that 25–38% of participating lab personnel have been involved in an accident or injury in the lab that was not reported to the supervisor/principal investigator (PI)[23–25].

Table 1 | A partial list of researchers killed in laboratory accidents at academic institutions (2008–2018)

Year	Institution	Location	Accident description
2018	Jiaotong University	Beijing, China	Three graduate students (names unknown) killed during an explosion while researching wastewater treatment
2018	Indian Institute of Science	Bengaluru, India	Manoj Kumar killed in high-pressure hydrogen cylinder explosion
2015	Tsinghua University	Beijing, China	Meng Xiangjian, postdoctoral fellow, killed in hydrogen explosion
2015	University of Health Sciences	Phnom Penh, Cambodia	Huy Siep killed when flammable gas ignited
2014	Texas A&M University at Qatar	Doha, Qatar	Hassan Kamal Hussein killed in explosion in petroleum lab
2012	Unknown university	Shanghai, China	Graduate student (name unknown) opened a poison gas cylinder and died from inhalation
2011	Yale University	New Haven, USA	Michele Dufault died during a lathe accident
2009	University of Chicago	Chicago, USA	Malcolm Casadaban died from exposure to plague-related bacterium
2008	UCLA	Los Angeles, USA	Sheri Sangji died from burns caused by ignition of tert-butyllithium

Adapted from ref. [14], Laboratory Safety Institute.

Contributing factors in laboratory accidents

Given the lack of research on the prevalence and incidence rates of academic lab accidents, it is perhaps not surprising that there is a similar lack of research on what causes lab accidents. Contributing factors to lab accidents can be conceptualized as occurring at multiple levels: risks associated with the materials or equipment being used, risks related to the skills, knowledge and choices of the research personnel doing the study, characteristics or qualities of the PI and the research lab in which the research is occurring and risk factors arising from the departmental or institutional level.

Risks associated with the materials being used have received the most attention in the laboratory health and safety literature. For example, there have been publications about specific reagents such as diazomethane, organolithiums or dimethyl dioxirane[26–29];

these reports are usually presented in the context of why a new methodology is safer or more effective. Discussions on particular reagents are mostly found only in the blogosphere[30,31], or in ever-growing compendia of reagents[32,33] (https://www.rsc.org/merck-index). However, safety information about reagents is not typically required by journals in the discipline. In 2016, Grabowski and Goode found that only 8% of the 726 chemistry journals they identified required safety factors to be mentioned in the manuscript[6]. The authors specifically looked at mentions of 11 target compounds that are known to be hazardous (including *tert*-butyllithium); these compounds were mentioned 107 times but only one article provided cautionary information.

If institutions are not providing comprehensive safety training on the use of reagents, which seems to be the case (see below), it becomes untenable for authors to assume that readers will be aware of the risks associated with particular compounds. This assumption becomes increasingly dangerous as more and more chemistry research is conducted around the world by inexperienced students and trainees. Starting in 2017, the ACS mandated that all experimental publications provide warnings for current or new hazards or risks[34]. However, this recommendation was tempered by the use of the phrase 'as appropriate', meaning that the inclusion of safety information is at the discretion of the authors and reviewers. A follow-up to the work of Grabowski and Grave would be informative as to whether the change in policy has changed the content of articles or has been enforced by the journals.

We could not find any studies anywhere that looked at how skills, knowledge, experience or attitudes of the research personnel are associated with the occurrence of lab accidents or other proxy variables (for example, near-misses). Similarly, there have been no studies investigating the occurrence and recurrence of accidents within specific departments or universities, nor has there been research looking at the role of situational factors in causing accidents, such as time of day (for example, late at night). The most complete research to date on the causes of academic lab accidents comes from the previously mentioned epidemiological study of Colorado chemistry departments for incidents occurring between 1966 and 1984[20]. Hellman, Savage and Keefe examined demographic characteristics of victims, details about research activities, type/location of injury, time of day, and time of year for 574 accidents. The value of this data to the contemporary research laboratory is questionable. Most incidents occurred during undergraduate teaching labs and many involved now-obsolete techniques (for example, mouth-pipetting).

There are also a number of historically based factors that limit the current applicability of the results: the majority of accidents happened during afternoons in the academic year, likely because this was when those universities offered undergraduate labs; and most injuries were to men, primarily because a much greater proportion of the undergraduate student population at that time were men. However, the study's authors highlight the contribution of human factors to lab accidents and call for additional research, saying "Of all the variables in accident prevention, the human behaviour variable, even with education, was the hardest to control"[35,36]. The study has never been replicated or updated since it was published and, we note with dismay, has only been cited 7 times according to independent Web of Science, Scifinder and Google Scholar searches conducted on April 5, 2019.

Case studies have been published in response to significant incidents and have typically resulted in the creation of reaction- and equipment-specific guidelines. For example, case studies have been published about Sangji's death[37], the explosion at Texas Tech[11], a gas leak at the National University of Singapore[38], the mishandling of a drum of radioactive material[39] and a sucrose-acid explosion at an unnamed university[40]. These case studies often take a comprehensive look at the multifactorial contributors to the accident at the individual, laboratory and institutional levels. However, this multi-level approach is not characteristic of safety research in general, nor of the implementation of safety policies in chemistry departments, though it should be. Researchers in the wider field of occupational safety have suggested that accidents are most likely to occur when multiple individual and system failures align (that is, the 'Swiss cheese' model of accidents)[41]. These case studies and reagent-specific studies have not led to more comprehensive research, a deeper conversation across the academic discipline or a broader examination of accident causes, despite explicit calls to do so. Fundamentally, case studies represent a collection of anecdotes[42], which may be informative and useful in specific situations and with specific materials, but represent an insufficient basis for the creation of wider evidence-based safety policies and procedures. Case studies play a valuable role in building the evidence base, but they are usually intended to be the launching point for broader analysis, not the end-point as they have been to-date in the world of academic lab safety. In fact, the bulk of these publications appeared in the *Journal of Chemical Health & Safety*, which is not completely indexed in SciFinder, despite being a flagship publication associated with a division of the ACS. Such considerations make this work difficult to find even for those scientists who actively seek it.

Attitudes about safety and behavioural practices

There has been some research on the attitudes and beliefs of lab personnel regarding safety in the lab. For the most part, these studies tend to suggest that researchers have generally positive views towards the concept of lab safety and related concepts. Wu and colleagues in Taiwan assessed perceptions of safety leadership in 465 lab employees; respondents rated levels of 'safety coaching', 'safety caring' and 'safety controlling' at their institution quite highly[43]. In a study of 85 staff, faculty and grad students, Steward, Wilson and Wang found generally positive attitudes about safety culture in the lab, that is, employees' perceptions, attitudes, and beliefs about risk and safety[44]. A large majority of participants in Ayi and Hon's study (88%) described safety as a high priority in their labs[22]. Schröder and co-workers found that over 90% of researchers felt that their labs were a safe place to work[45]. Although these studies are encouraging and potentially relevant to the occurrence of lab accidents, the role of abstract ideas such as safety culture, safety climate, safety leadership, safety coaching and subjective feelings of safety is of limited utility without these constructs being validated against objective measures such as frequency of accidents and injuries, or even of proxy measures such as inspection violations. In other words, it is not clear if individuals who value safety and believe that their workplaces are safe actually make safe choices in their laboratory practices. To date, there has been no research on the correlations between safety attitudes and safety practices.

In contrast to these optimistic findings about safety beliefs, research results regarding behavioural safety practices are concerning. The results from several studies have suggested that researchers are disinclined to conduct safety assessments prior to conducting experiments. In Ayi and Hon's study, 27% of participants, active experimental researchers, stated that they never conducted any kind of risk assessment before performing laboratory work[22]. In another study, half of respondents did not search for, or use, safety information in developing experimental procedures, yet 80% considered the existing available information adequate to support risk assessment (suggesting that participants generally thought the information to be sufficient but were disinclined to use it for other, unidentified reasons)[46]. In Schröder and co-workers' comparison of researchers in different settings, academic researchers were the least likely to assess risk (only 18% reported doing so) compared to industry (43%) or government (36%)[45]. To be fair to academia, the low rate of risk assessment identified in this study by researchers in industry and government is also troubling.

There have also been a few studies on the use of PPE, and again, the results are difficult to interpret given that the general positive attitudes towards safety shown in these studies. In a study of undergraduates in teaching labs (arguably, the easiest cohort to observe and control), Sieloff and coauthors found that 94% of students consistently reported wearing eye protection but 65% said they never wore gloves[24]. These findings are similar to those of Ayi and Hon, who found that only 40% of their participants and academic researchers reported wearing PPE at all times when working[22]. Schröder and colleagues found that researchers in academia were less likely to wear lab coats (66% consistently wore them) or eye protection (61%) than industry (87% and 83% respectively) or government employees (73% and 76%)[45]. Again, these numbers are a cause for concern.

From a methodological standpoint, the exclusive use of self-report data in these studies is troubling as results are likely to be inaccurate due to social desirability bias in participants' responses (that is, the tendency of respondents to answer questions in a manner that will be viewed favourably by others)[47], a factor that has not been acknowledged or addressed in any of this research[48]. For example, researchers know that they should be wearing PPE and may therefore intentionally or unintentionally inflate the numbers they report in studies; a more accurate estimate of PPE usage, which could be gathered through observational studies (but so far has not), may be much worse. However, without proper data, we cannot say with any certainty how the use of PPE relates to accident frequency and/or severity. It may be the case that the semblance of protection can encourage riskier behaviour. For example, research has shown that the use of bicycle helmets is correlated with increased risk of accident[49], consumers tend to make higher-calorie choices when provided with calorie counts at restaurants[50] and beachgoers often choose to swim outside of designated safe areas on beaches[51]. The use of PPE might encourage researchers to take more or greater risks and therefore increase the rate or severity of lab accidents. These are the types of questions that should be addressed by researchers of academic lab safety.

Commentators on academic lab safety have noted the role of human factors and remarked on their importance in safety behaviours[52]. Some have even labelled the cognitive biases at play in safety issues or made safety recommendations based on psychological principles of habit development[53]. Hendershot expressed concern at researchers' tendencies to believe that activities must be safe if they are done routinely and nothing has gone wrong, thus ignoring the base rates of accidents[36]. He cautioned, "Our personal experience in a few thousand work hours is not statistically relevant when actual performance of the process industries is in the range of a few fatalities in hundreds of millions of exposure hours." Human factors have frequently been cited in the write-ups of incident case studies. For example, Schmidt mentioned the bystander effect (that is, the tendency of individuals to offload responsibility for intervening in a critical situation when others are present[54]) in describing the circumstances that led to a gas leak at a research institute in Singapore[38]. The results from several studies suggest that many research personnel see the level of risk in their laboratories as low. For example, 59% of participants in Ayi and Hon's study thought that the level of risk associated with their work was low or very low[22]. It would also appear that decision-making with regards to PPE is heavily based on respondents' own assessment of risk: at higher levels of (self-assessed) risk, respondents in Schröder's study said they were more likely to don the appropriate PPE.

Given the likely impact of individual biases, ensuring perfect access to information and training (for example, Bretherick's handbook, ACS guidelines, departmental policies and laboratory policies) and making equipment available is not likely to change outcomes without a better understanding of the psychology of safety decision-making[46,55]. These resources are currently available to many researchers and are not being used. Behavioural data must be collected to inform new practices in training. The relationship between the perception of risk and safety attitudes and behaviour needs to be studied and addressed. However, to date, the champions for safety have been natural scientists and engineers whose research expertise is not in social science methodology and who may be unfamiliar with important and relevant psychological constructs (such as social desirability in responding). The studies examined for this Review article, as noted throughout, suffer from flaws that compromise the validity, reliability and generalizability of their findings where policy is concerned.

More often than not, the consideration of human factors has tended to centre on blaming victims for their behaviours that led to or aggravated an accident, exemplified in the case of Sangji[56]. Although many write-ups focused on the fact that she did not think to use the lab shower when her shirt caught fire, in fact, neither of the two postdocs who assisted her in the aftermath of the incident thought to do so either[1]; the tendency of individuals to respond inappropriately in the face of a medical emergency is a well-documented phenomenon, but this has not been accounted for in the development of laboratory safety policies[57,58]. Or, as Hill and Finster put it, "It's easy to blame the individual and not consider why the person acted in this way"[59]. This attitude seems to be widespread across the profession. In their study of the contributing factors to lab accidents, Hellman and co-workers interviewed chemistry educators, who reported that most accidents happen because students are careless and do not listen to instructions[20]. The tendency towards victim-blaming has often led to a perception of post-incident investigations as punitive rather than learning experiences[39], thus increasing negative attitudes towards safety policies and procedures, poisoning the attitudes of generations of students and increasing the under-reporting rate.

Safety training research

Attitudes and beliefs about lab safety may be shaped as early as during undergraduate study, or even earlier[60], and there have been numerous calls for safety training to be incorporated into the undergraduate curriculum in a more meaningful way[13,61–63]. Consequently, there is slightly more research on safety training for undergraduate students enrolled in teaching labs compared to research labs[61,64–74].

Several studies have looked at program-wide safety initiatives that incorporated a variety of strategies. Many of these published studies have been done at small primarily undergraduate institutions (PUIs) rather than at large research-focused schools, although there are a few notable exceptions[15,73,75,76]. Common elements to these programmes include handouts, didactics, the creation of safety databases, self-study programmes, laboratory exams and quizzes, use of safety contracts and the creation of safety-focused courses at some universities[63,65–67,73,77]. Other researchers have looked at the use of more specific strategies for enhancing safety, including safety planning documents[78], black lights to demonstrate issues of lab cleanliness[71], scavenger hunts as a training strategy[64], student safety teams[72] and personalized safety videos[68]. Others have made comparisons between online and in-person safety training programmes[61]. Shariff and Norazahar had students report on their peers' safety behaviours and found a reduction in all of the issues researchers identified (for example, use of PPE, keeping work spaces clean, horseplay) over the study time period[79], with the exception of cell phone use.

Research on the safety beliefs and practices of undergraduate students is important. Our concern is that many undergraduates quickly learn to see safety training as an institutionally mandated hassle. The risks are often minimal by design, and the information is provided out of context and can appear to be overly restrictive and possibly silly. This negative attitude towards lab safety may be of little consequence in undergraduate teaching labs that are carefully controlled and involve few hazardous reagents. However, should these students continue on to graduate school and further work in academic research labs, a casual disregard towards safety may be a much greater liability when they are working with more dangerous reagents and processes. First impressions are extremely important and can cement attitudes and approaches early.

Unfortunately, much of the existing research on safety training in undergraduates is of questionable validity with regards to evidence-based policy-making on a wider scale or outside of the setting in which the data was gathered. These studies rarely include control groups or randomization to the intervention to ensure that observed changes are due to the programme alone and not to other factors. Studies also typically examine the combined effect of several initiatives simultaneously making it impossible, if there is any measurable change, to disentangle the causative contribution of the interventions. These studies generally do not include pre- and post-measures to assess the efficacy of the program. Because they lack this behavioural follow-up, it is unclear which safety training interventions lead to increased knowledge, better retention, increased compliance with safety rules, a decreased rate of incidents or better results in laboratory safety inspections. The one study that did look at the effects of specific intervention sessions found increases in (self-reported) safety knowledge, safety perception and safety attitude, but crucially, no corresponding increase in safety behaviour[70].

The safety programs are usually implemented only at one institution, meaning that it is unclear whether these initiatives would be feasible or applicable elsewhere, and the research is conducted by those who established the safety protocols, making results susceptible to bias. Our intention in critiquing the methodology of these studies is not to throw the metaphorical baby out with the bathwater. The efforts of these researchers who have taken time out of their primary research programme to investigate these issues are laudable, and we would not expect professors whose primary expertise is in the natural sciences to have a detailed knowledge of psychological or pedagogical research methods. Our point is rather that collaboration with social scientists may be the key to building and improving on this area of the research literature and that methodological errors can be readily addressed in the study design, with no more effort on the part of the researchers. At the same time, social scientists, who are not experts in the materials and processes employed in the laboratory setting, need to work with the natural scientists to design the studies and the interventions. This research, by its very nature, requires an interdisciplinary approach.

There have been far fewer studies about implementing safety improvements in academic research labs. Some papers have been published on how to perform safety investigations[80], how to learn from close-calls[81,82] and how to design hazard-analysis systems[83], all indicating that these basic practices are not universally implemented. Others have reported on risk reduction strategies, including systematic approaches to safety management and risk assessment[83], the use of facility login software[84], the creation of a chemical safety library[85] and the creation of a website designed to share safety information and accident findings[15]. A collaboration between the University of Minnesota and Dow Chemical Company resulted in a safety initiative that included regular lab tours with reports to PIs and Laboratory Safety Officers (LSOs), the use of posters advertising PPE usage and Standard Operating Procedure-compliance, regular communication of safety updates via e-mails and website updates, a 'cleanup' week and training regimen for LSOs[76]. Staehle and colleagues studied the implementation of behavioural strategies in a research lab, including twice-daily inspections by lab members, the use of discussions and quizzes during lab meetings and the use of an overnight reaction form[75]. Huising and Silbey described the 5-year implementation of a comprehensive management system involving lab inspection teams, the registration of PIs' labs on a database and completion of safety training courses[35]. Other publications on safety training have looked at how to train staff[56], including custodial and maintenance workers who work in laboratories[86].

Again, the same methodological issues that plague research on undergraduate safety programmes are also true for academic research labs (for example, lack of control groups and randomization to interventions, inclusion of several interventions at once, no measurement of objective data such as accident frequency or inspection violations) and make interpretation and generalizability of results questionable. We have not been able to locate any studies or articles investigating how PIs train their research personnel, or on how PIs report that they themselves were trained. This lack of research with regards to safety training in academic settings means that in most instances, safety training is a product of institutional memory, anecdotes and, as James Gibson from the Office of Environment, Health, and Safety at UCLA put it, the 'application and misapplication of common sense' rather than guided by a standard evidence base[87]. Throughout the investigative report on Sangji's death at UCLA, it was clear that training was largely conducted through informal interactions and the passing along of knowledge. Although this is an essential component of training and knowledge, it should supplement rather than replace the use of formal training, institutional and laboratory-specific standard operating procedures, protocols and information from manufacturers, professional societies and compendia of reagents. This informal approach to training is particularly troubling because the knowledge being passed down may not conform to best practices, as was clear from the report on Sangji's death[1].

A few studies have been done about perceptions around safety training by academic researchers. In a survey of 2,400 researchers led by *Nature* and UCLA, 60% of respondents reported having received safety training on specific hazards or reagents[21]. Schröder and co-authors found that 70% of researchers in academic settings received safety training, but only 26% were trained within 30 days of starting experiments (the average length of the gap between starting work and receiving appropriate training was not reported but is certainly worrying)[45]. This training was usually conducted by Environmental Health and Safety Officers, with only 35% of participants saying that they had had additional training from their PI. In a smaller study of 85 participants[22], 47% of participants did not know how often safety inspections were performed in their labs, 35% did not have access to data or records regarding their lab's safety and whether or not it complied with legislated requirements and 9% did not know how to handle an emergency such as a fire or a spill. Again, an additional concern here is that these results reflect the self-perception of participants that they could handle a fire or spill, not an objective evaluation of their capacity to do so. Another study found that 25% of researchers had not been trained in the specific hazard with which they worked[45]. One study showed that only 10% of students, postdoctoral fellows, faculty and staff felt that their safety training had prepared them to assist others and to intervene when others engaged in unsafe behaviours[76].

Research on safety training, or lack thereof, stands in stark contrast to findings suggesting that many researchers feel their lab is a safe environment. Although anywhere from 15–30% of researchers report having been involved in an accident or having sustained an injury, and that a large percentage also say that they have not received adequate or timely safety training, most studies have shown that researchers report feeling safe in their labs, perceive the risk level in their laboratories as low and describe their institution as having a good safety culture. What are we to make of this discrepancy between objective injury data and subjective feelings of safety? Our interpretation is that risky practices and a cavalier attitude toward safety are so normalized within academia that the low standards in the field are not troubling or even apparent to those on the inside.

Barriers to safety research

Researchers repeatedly state that laboratory safety is important, but knowledge about laboratory safety has not improved over the past decades[22]. Faculty attitudes appear to be one of the main barriers to change, dating back to the establishment of the first modern academic labs in 1840s. According to Kekulé, in the 1840s, Liebig welcomed him into his lab as a graduate student by saying: "If you want to become a chemist…you have to ruin your health. Who does not ruin his health by his studies, nowadays will not get anywhere in Chemistry"[88]. The belief that injuries, accidents and near-misses are 'just part of the job' remains common and current across the profession[20,21,89,90]. Scherz commented on the element of rebel as scientific hero portrayed in the autobiographies of some prominent molecular biologists[91]. This attitude towards risk has some corroboration in the research. In a series of interviews conducted with chemistry educators, participants reported that minor accidents were of no importance[20]. The idea of working alone in the lab at all hours of the day, every day of the year is still considered by some academic supervisors to be a positive and desirable attitude in trainees[19]. (Note that Sangji's accident occurred on December 29, during the winter holiday break).

Many commentators have remarked that the most important barrier to the initiation and implementation of comprehensive safety programming is the attitudes of PIs[16,36,92–96]. In the *Nature*/UCLA survey of 2,400 researchers, the most commonly identified barriers to improving lab safety included 'time and hassle', apathy, lack of understanding of safety requirements, lack of leadership, and a focus on regulatory compliance[21]. Other faculty members have cited a lack of knowledge, a lack of funding and disagreements about safety policies as reasons for non-adherence to mandatory policies[9]. In one study of lab personnel, barriers to safety improvements included time and hassle factors, apathy, inadequate training and competing priorities[22]. The issue of 'academic freedom' is often raised as an objection to safety practices. One study found that 15% of researchers believed that safety regulations interfered with productivity, and 23% believed that they impeded the scientific discovery process[45].

The community has made definite efforts to improve policy in the past 10 years. This includes the ACS's adoption of safety as a core value, a mandate that safety information be included in journal articles as appropriate, the appointment of a manager of safety services and an effort to improve safety education across the educational spectrum. This is laudable, but it is unclear whether these efforts are making an objective difference. Many of the studies we have cited throughout this article regarding safety behaviour are all recent and refer to post-UCLA incident practice. Despite efforts from the ACS and other bodies, it is unclear whether this change in attitude is being integrated into the practice of academic chemical research, especially when one considers the high levels of resistance to safety measures observed by Schröder and colleagues in 2016[45].

Seemingly negative attitudes towards safety practice may be due to a perception by many scientists that workplace inspections are focused more on procedures and regulatory compliance than with a true concern for laboratory safety[45,59,78,87]. As Kapin pointed out, "health and safety programs for laboratories are typically oriented around specific regulatory requirements, even though hazards in laboratories seldom respect these boundaries[78]". Possibly one of the major issues may be the perception of EHS officers as academic 'interlopers'[91], who are not seen by researchers as having the practical experience necessary to elicit compliance with their recommendations. EHS officers working at UCLA at the time of Sangji's accident reported that they were aware of inconsistent use of PPE in research labs but had no power to impose sanctions or address non-compliance[1].

Simply put, the academic discipline does not prioritize safety. Following the UCLA incident, Langerman made a number of recommendations for how safety issues could be addressed by students, faculty, laboratory staff, environmental health and safety officers, funding agencies, professional societies and the ACS[97]. His growing exasperation over time was obvious to readers[7,97,98], and he recommended ensuring the compliance of recalcitrant PIs by taking accident reports, laboratory investigations, and safety policy compliance into account for promotion and tenure and the allocation of departmental resources. He also suggested that grant funding and prizes should be denied to PIs with poor safety records. Although these ideas have been taken up by other commentators[91], so far these recommendations have not been implemented. We are not aware of any PIs who have been terminated or denied funding because of a poor safety record, so these policy recommendations have not appeared to have any influence to date.

A call for action

The state of academic safety research is unconscionable and cannot be allowed to continue. Data is required to develop evidence-based policies to address each of the issues we have raised in this article. Currently, there is no central database or organization responsible or funded to collect and analyse the annual number and characteristics of accidents in academic research labs. Data is needed not only on the headline-grabbing accidents that result in fatalities or hospitalizations, but on any close-calls, regardless of the occurrence of injury or significant property damage as the differences between near-misses and major catastrophes may be primarily due to good luck rather than good management. We need to know how big of a problem underreporting of accidents is and what factors are associated with underreporting. Data of this type would enable the identification of variables associated with accident frequency and severity and would help to determine the most appropriate countermeasures.

We need more information about the causes of academic lab accidents. We need to know how, where, when and to whom accidents happen. We need to know what contributes to accidents at the level of the individual, the lab, the department and the institution. We need to know the impact of these accidents on the victim, their friends and family members, their labmates, fellow students, faculty and staff, and the wider academic culture and institutional community. Do students drop out? Do they change their career plans? Are there mental-health repercussions for students, labmates, faculty members, staff members or other members of the university and research community? Is the climate different in universities where there have been multiple incidents? We have none of this information.

We need to delve further into attitudes and beliefs about safety. We need to know how these are correlated with demographic variables, training and lab experiences. We need to know how safety attitudes develop and how and when to intervene such that students view safety as a fundamental priority within science rather than a hassle. We need to know how beliefs and attitudes relate to behavioural practices with regards to PPE usage and risk assessment and how best to address discrepancies to keep personnel safe.

We need more research into safety training. There are two key domains of inquiry here. The first focuses on process: How is training currently done at different institutions? Are there more effective strategies for conveying the content? How should comprehension be evaluated? Under what circumstances is information retained? The second focuses on content: What should the content include? How should new situations be evaluated for safety? Most importantly, both strands of the research need to converge on the most important question: how do training interventions correlate with frequency and severity of accidents in labs?

However, while actuarial data and guidance in training procedures would be of great benefit, it will not necessarily help address the fundamental problem of culture, that is, the 'fiefdoms' so omnipresent in academic settings[99]. We need to identify the barriers that prevent the systematic acceptance of the necessity for the learning and application of safety principles among students, faculty and staff. We need to understand what interventions, rewards and sanctions are required to overcome these barriers. We need to better understand the social scripts around scientific identity and culture. We need to understand how best to implement meaningful and impactful safety training starting in first year undergraduate level (or earlier) and how to build upon it continually throughout the degree and into graduate and postdoctoral training and faculty mentoring. We need to use proper methodology to determine the effectiveness of the training methodology and look at quantifiable outcomes. We need to determine how to address inherent challenges to safety research and training in the academic setting, such as high turnover of staff and students[56].

Conclusions

Currently, there are 45 universities in Canada offering graduate chemistry programmes with a total of approximately 880 research groups in chemistry departments based on a hand count conducted on December 29, 2018. There are 432 research intensive (R1, R2 and R3) universities in the United States; although a count of research groups would be challenging, we would expect around 10,000 research groups. As graduate education spreads around the world, and with the exponential growth of programmes in China and India, the number of individuals involved in academic chemical research is set to expand. Currently, we are operating completely in the dark with regards to safety policies in both training and practice. We do not even know how many people are hurt every year and how badly, nor how great the damages are to laboratories, buildings and equipment. We simply have no idea about the scale of the issue — on the very day this section of the article was written, three graduate students were killed in a research-lab explosion at Beijing Jiaotong University[9], and while the article was under review, another accident occurred at UCLA that involved a brief hospitalization[100].

The benefits of establishing academic lab safety research programmes would be substantial. Ultimately, the goal would be to decrease the rate and severity of accidents in academic labs, ensure that lab personnel stay safe and healthy, and that equipment, laboratory and buildings are protected. This is also likely to have a spillover effect into industry — better-trained, more safety-conscious students would make better industrial employees. Undoubtedly, there would be financial savings related to the cost of accidents, insurance rates and lawsuits.

Despite calls for safety studies to form a central part of chemical research including tenure-track positions at major research universities[63], and an increased understanding and interest in chemical safety studies by experimental research professors[15], we could not identify any scientist whose principle mandate was the study of chemical safety. At present, we know of no tenure-track positions in science safety at any global research university. Despite the need for these positions, we are not optimistic that the university community will address this situation, but sincerely hope to be proven wrong. If action is not taken soon, academic chemical research may come to be seen as too risky for some institutions from a liability perspective: if we as a discipline do not take action, action may well be taken for us.

Scientific research dealing with new methods, new materials and a constant influx of new and inexperienced trainees will always be potentially hazardous, but we must do what we can to manage those risks that can be managed. In 2009, Langerman said, "I have come to the disheartening conclusion that most academic laboratories are unsafe venues for work or study. I have concluded that only by a major change in the way we practice laboratory safety can we improve the situation"[97]. In his profile of major incidents in research labs, he noted with depressing repetitiveness that in most cases, virtually identical incidents occurred at the same institutions within 10–15 years, resulting in the destruction or temporary closure of the buildings[98]. More than ten years after Sangji's avoidable and tragic death, we have not made nearly enough progress into understanding and addressing academic lab safety issues. We hope a ten-year follow-up to this review will conclude differently.

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