EXPLORING GOAL CONFLICTS AND HOW THEY ARE MANAGED IN A BIOMEDICAL LABORATORY USING RASMUSSEN’S MODEL OF BOUNDARIES

Viji Vijayan | LUND UNIVERSITY

EXPLORING GOAL CONFLICTS AND HOW THEY ARE MANAGED IN A BIOMEDICAL LABORATORY USING RASMUSSEN'S MODEL OF BOUNDARIES

Viji Vijayan

Lund 2018

EXPLORING GOAL CONFLICTS AND HOW THEY ARE MANAGED IN A BIOMEDICAL LABORATORY USING RASMUSSEN'S MODEL OF BOUNDARIES

Viji Vijayan

Number of pages: 61
Illustrations: 19

Keywords
Rasmussen's model, Resilience, Degrees of Freedom

ABSTRACT

Occupational health and safety management systems are widely used as a systematic approach to managing occupational health and safety in organizations. One important element of which is the development of Standard Operating Procedures to ensure uniform written safety procedures throughout the organization. Such procedures are sometimes restrictive and inadequate to deal with the dynamic and changing workplace of today. Workers will realize that there are degrees of freedom (Rasmussen, 1997) available to them and they will use it to adjust their work such that they remain productive in spite of other constraints like work load, resource availability, restrictive safety procedures, etc. Rasmussen used a model of boundaries to plot this variability in performance, in which the operating point is the point in the space within three boundaries where a person performs the work. The three boundaries he described are economic failure, workload and functionally acceptable performance.

This project focuses on applying Rasmussen's model of boundaries to a biomedical research laboratory by gathering interview data from fifteen participants. The three boundaries identified were scientific output boundary, workload boundary and safety boundary. The results show that the most central goal was to be the first to publish and this formed the scientific output boundary. Factors contributing to workload were long and tedious nature of experiments, multiple projects, resource availability and time-consuming safety regulations. The workers had developed good resilience building methods to ensure that they did not cross any boundary. Mental risk assessments before deviating from safety procedures, team work, experience and familiarity were constantly used to remain within the boundaries. The very dynamic nature of the work was evident by the fact that the above methods were used not to avoid just one boundary but all three. For example, team work helped to remain safe while ensuring that the experimental results were not jeopardized at the same time keeping the individual workload manageable.

Using the information obtained in this project it is clear that a strict regulation-based approach is inadequate to deal with the dynamic demands in a biomedical laboratory and a customised portfolio of rule-based and risk assessment-based approach would be more suitable. The rule-based organization-wide instructions will invite compliance when they are correct (commensurate on risk) and rewarding. These will always lack the requisite variety needed to deal with constantly changing work demands which need to be dealt with using local risk-based resilience building practices. The workers had already developed good resilience building methods and it would be important to build on this through properly tailored training.

Riskhantering och samhällssäkerhet
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund

http://www.risk.lth.se

Telefon: 046 - 222 73 60

Division of Risk Management and Societal Safety
Faculty of Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

http://www.risk.lth.se

Telephone: +46 46 222 73 60

TABLE OF CONTENTS

ABSTRACT 4
Table of contents 6
List of tables, figures and appendices 8
Glossary 9
Introduction 10
  Background 10
  Literature Review 11
  Aim of the Project 15
  Organisation where research is undertaken for this thesis 15
Materials and Methods 17
  Organization where research is undertaken for this thesis 17
  Ethics 17
  Data Collection 17
  Identification of themes 17
  Procedure 18
  Demographics of the Participants 18
Results 20
  Accidents encountered 21
  Plotting of Rasmussen's model of boundaries for a biomedical laboratory 23
  Scientific Output Boundary 25
  Workload boundary 27
  Gradients related to scientific output boundary that could push the OP closer to the safety and workload boundary 28
  Gradients related to workload boundary that could push the operating point towards the safety and scientific output boundary 30
  Safety Boundary 32
  Reasons for Deviating from SOP 33
  Examples of short cuts taken and the boundary that is being avoided by the participants 35
  Resilience Building Methods 38
  Mental Risk Assessment 39
  Team Work 40
  Experience and familiarity 42
  Safety Training 43
Discussion 47

Conclusion 53
References.. 55
Appendix.. 57

LIST OF TABLES, FIGURES AND APPENDICES

Figure 1: Rasmussen's model of boundaries	9
Figure 2: Rasmussen's model of boundaries and resilience	10
Figure 3: Demographics of participants	16
Figure 4: Hazards faced by participants	17
Figure 5: Length of biomedical experience and the number of accidents encountered	19
Figure 6: Rasmussen's model of boundaries for a biomedical laboratory	20
Figure 7: Cause of failure of experiments	22
Figure 8: Pressure gradients created while avoiding moving past the scientific output boundary	25
Figure 9: Pressure gradients created while avoiding moving past the workload boundary	27
Figure 10: Gradients that can affect the operating point	31
Figure 11: Examples of deviation from standard operating procedures	33
Figure 12: Injury statistics	45
Table 1: Types of hazards faced by participants	18
Table 2: Factors contributing to the scientific output boundary	21
Table 3: Factors contributing to workload	23
Table 4: Participant's opinion about standard operating procedures	29
Table 5: Reasons for deviating from standard operating procedures	30
Table 6: Resilience building methods	35
Table 7: Methods of learning experimental techniques and safety	40
Appendix A: Participant informed consent form approved by the University Institutional Review Board	53
Appendix B: Interview questions approved by the university Institutional Review Board	54

GLOSSARY
(Alphabetical Order)

BTCU:	Borderline Tolerated Conditions of Use
DIY:	Do it yourself
MD:	Doctor of Medicine
OHSMS:	Occupational Health and Management Systems
OP:	Operating Point
OSHAS 18001:	Occupational Health and Safety Assessment Series 18001
PCR:	Polymerase Chain Reaction
PDCA:	Plan-Do-Check-Act
PhD:	Doctor of Philosophy
PI:	Principle Investigator
SDS:	Sodium dodecyl sulphate
SOP:	Standard Operating Procedures

INTRODUCTION

Background

Occupational health and safety management systems (OHSMS) are widely used as a systems approach to managing occupational health and safety in organizations. Such systems typically provide a framework for organizations to develop policies, processes and procedures to ensure the health and safety of its employees (Robson et al., 2007). One of the popular OHSMS is Occupational Health and Safety Assessment Series (OHSAS) with the British OHSAS 180001 emerging as a very popular system. According to reports in 2009 nearly 56,251 organizations had been certified to this standard double the number in 2006 (Hasle & Zwetsloot, 2011). OHSMS is modelled on the concept of Plan-Do-Check-Act cycle (PDCA), which is a repetitive cycle to ensure continuous improvement in the organization's performance, in this case safety performance (Dejanović & Heleta, 2016). Using this concept, the OHSMS facilitates management of risk associated with the activates of the organization, by implementing among several other elements, risk assessment and risk mitigation through the development of practices and procedures which are standardized through the organization. Thus, an important element of the OHSMS is hazard identification, risk assessment and mitigation, and development of Standard Operating Procedures (SOP) to ensure uniform written safety procedures throughout the organization. Such SOPs have to be aligned to the parent organization and other applicable regulations (Vijayan, Mahalakshmi, & Lee, 2013).

While the benefits of uniform SOPs throughout an organization are certainly well recognized its pitfalls, of being time consuming and restricting and reducing individual variation are also known (Amare, 2012). Organizations often face multiple goal conflicts that pull or push them in different directions. This will certainly trickle down to the sharp end workers who will have to make adjustments in how they work. Keeping in mind the goal of production, workers will realise that there are degrees of freedom available to them to perform the task and they will use these degrees of freedom to adjust their work such that they remain productive in spite of other constraints like work load, resource availability, restrictive safety SOPs, etc., (Rasmussen, 1997). SOPs are sometimes either inadequate or too restrictive to deal with the changing demands and workers often need to use their own local rationality and adjust the way in which they perform the tasks using the degrees of freedom available to them. This is very true in biomedical research laboratories, whose raison d'être is generation of new knowledge, technologies and discoveries. This makes them vulnerable to risks posed by hitherto uncharacterised hazards. Research laboratory workers are highly skilled and at the forefront of discoveries and have the most updated knowledge of the risks posed by the research. It is likely that they constantly use the degrees of freedom and adjust the way they work, even if it means deviating from SOPs, to remain both productive and safe in spite of workload and other constraints.

This study looks at the factors that contribute to the conflicting goals faced by biomedical laboratory workers and the methods they employ to remain both productive and safe. This has not been attempted in a biomedical laboratory and the information obtained can be used to supplement and strengthen the existing OHSMS approach.

Literature Review

Rasmussen used a model of boundaries to plot this variability in performance due to workers exercising their degrees of freedom in response to the changing demands of the sociotechnical system in which they work (Rasmussen, 1997). In this model, he visualized work as being done in the space within boundaries (figure 1) and likened the "situation-induced variations within the work space to the 'Brownian movements' of the molecules of a gas" (Rasmussen, 1987, p.189). Human behavior at work is strongly controlled by goals and constraints that individuals face in their everyday work life. These constraints and goals have to be taken into account when understanding how they work. According to Rasmussen, "aiming at such productive targets, however, many degrees of freedom are left open which will have to be closed by the individual actor by an adaptive search guided by process criteria such as work load, cost effectiveness, risk of failure, joy of exploration, etc." (Rasmussen, 1987, p.189).

The operating point (OP) is the point in the space within the boundaries where a person performs the work, in reality, the location of the operating point will not be not easy to plot accurately. Rasmussen also described gradients (effort and cost gradients) which the workers will need to identify and counter, because if left unheeded it could push the OP to cross one or more boundary. Therefore, recognizing and understanding the boundaries and gradients will give workers the opportunity to anticipate and avoid moving past the boundaries, in other words build resilience.

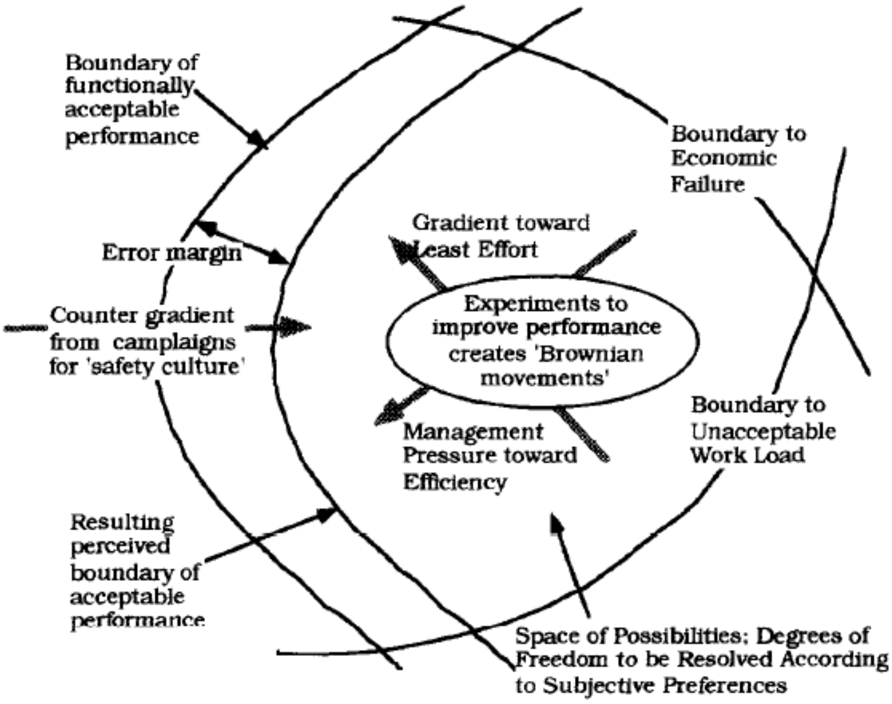

Figure 1: Rasmussen's model of boundaries:

The figure shows the model drawn by Rasmussen reproduced from (Rasmussen, 1997)

Woods and Hollnagel (Woods & Hollnagel, 2006) explain that hindsight colors the way organizations handle safety and "we are consequently constrained to look at the future in the light of the past" (Woods & Hollnagel, p. 251). In order to understand failure, one must study success to see how people adapt to remain safe in the world faced with hazards, trade-offs and conflicts. The authors write "success belongs to organizations, groups and individuals who are resilient in the sense that they recognize, adapt to and absorb variations, changes, disturbances, disruptions and surprises – especially disruptions that fall outside of the set of disturbances the system is designed to handle" (Woods & Hollnagel, p. 277).

Hale and Heijer have defined resilience not only as the ability to recover from a failure but also to anticipate and prevent failure and eloquently likened it to a medieval ship where lookouts are constantly on the watch for danger while the ship is sailing (Hale & Heijer, 2006). In a bowtie model of accident scenarios, resilience would be on the right hand side as well as the left hand side. The authors have projected this definition on to the Rasmussen's model of boundaries described in figure 1, adding a X and Y axis to the figure as shown in figure 2.

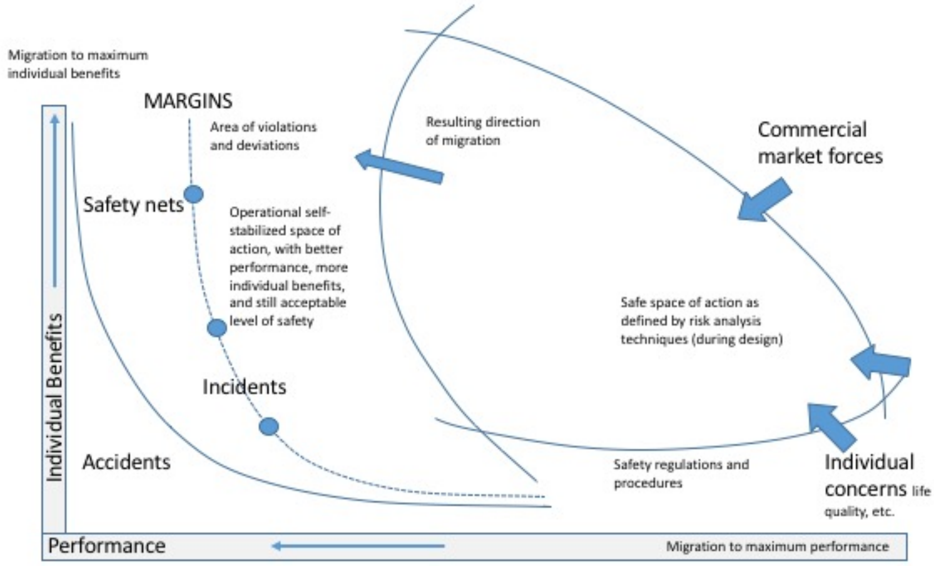

Figure 2: Rasmussen's model of boundaries and resilience (reproduced from Hale and Heijer)

This model has also been applied to study resilience in the way the Emergency Department staff adjusted to surges in patient volume (Nemeth, Wears, Woods, Hollnagel, & Cook, 2008). The authors explain that knowing where the operating point is in relation to the margins, especially of the functionally acceptable performance, requires both organizations and workers to develop a "keen awareness of its operations and variability in performance" (Nemeth, Wears, Woods, Hollnagel & Cook, p. 4). The authors explain how the Emergency Department staff coped by using known and newly thought-out methods in unusually difficult situations to gain control of it. It is through understanding the goal conflicts and methods used to address them that effective improvements can be planned.

Rasmussen's model of boundaries has also been used to measure resilience in the Dutch railway system (Siegel & Schraagen, 2014). The authors describe three boundaries and related pressures (gradient) that would affect the OP as: economic boundary/performance pressure, safety boundary/safety pressure and workload boundary/least effort pressure. They have attempted to plot the location of the OP in relation to the boundaries using quantifiable data and by viewing the model from above have plotted a slope to measure resilience.

The idea of projecting the definition of resilience on to Rasmussen's model of boundaries has been attempted before based on the above literature. However, this has not been attempted in a university biomedical laboratory. Biomedical research teams constantly encounter new technology or material; this creates a dynamic situation with changing risks encountered at work. This in turn, requires the individuals and team to be adept at recognizing and controlling the risks. Biomedical research teams work relatively independently within their own space and groups, thus providing a good place to apply Rasmussen's model of boundaries to study the factors contributing to the boundaries, gradients and methods that are used to anticipate and avoid (be resilient) moving past the boundaries.

Research teams are most challenged, with production pressure when working with novel ideas and material, because they want to be the first to publish. While publications are the main indicators of performance, safety is something that they have to constantly bear in mind, because one major lapse can end their career. A good example of such an occurrence is in the University of California, Los Angeles, where a 23-year-old research assistant died as a result of severe burns while working with a liquid called tert-butyllithium. The Principle Investigator's (PI's) stellar career suffered a great blow and the university spent USD 4.5 million on defending him (Van Noorden, 2011).

Perhaps it is the degrees of freedom available to the workers that allows them to anticipate and avoid failure thus making them resilient. In an attempt to answer this question, this project turns to Rasmussen, who has pointed out that today's workplace is very dynamic with changing risks, and the behavior of workers is inseparable from their working context; this is very true in a biomedical research laboratory. Today, in a biomedical laboratory, competence is not dependent entirely on formally-acquired knowledge, but also on heuristic know-how and practical skills acquired through experience, which allows workers to act quickly and effectively to prevent a harmful incident. Biomedical researchers constantly face new challenges through new viruses, new technology, and new applications, many of which have not even been characterized enough to understand the risk they pose. This project is aimed at understanding the boundaries and how biomedical workers ensure that they remain within the boundaries, when faced with the conflicting goals that pull them in different directions.

Aim of the Project

This project focuses on applying Rasmussen's model of boundaries to a biomedical laboratory in order to: a) identify the factors that contribute to the three boundaries; and b) identify the gradients that push the OP towards or away from the three boundaries.

Organisation where research is undertaken for this thesis

This project was undertaken in a US-style medical School, which has enrolled over 600 students in the MD and PhD programs. The School's strong biomedical research emphasis is evident in its five research programs and seven research centers that accommodate over 60 research teams. The School has established a School-wide Occupational Health and Safety Management Systems (OHSMS) to oversee all aspects of safety in the School and its activities. The OHSMS is modelled on the elements of the Occupational Health and Safety Assessment Series OHSAS 18001, which is an internationally accepted standard for occupational health and safety management systems. The School has successfully obtained OHSAS 18001 certification for the past five years.

Research in the School is organized into research programs, each of which has several principal investigators (PIs) working within a common field of research. As part of the School-wide OHSMS, each PI is also required to develop an OHSMS for his/her own laboratory, based on the OHSAS 18001 elements. The School has a Safety, Health and Emergency Management Department that works closely with the PI and his/her team members to ensure that the laboratory has developed and implemented a robust OHSMS. This includes identifying hazards and implementing control measures and SOPs, training programs, and other requirements in compliance with applicable regulations and laws.

Typically, the PI heads a research team in which the members possess a wide range of educational qualifications from undergraduate diplomas/degrees to PhDs, and a wide range of expertise based on their work experiences. Within the research team, the PI usually organizes workers into groups with a senior member mentoring and supervising the junior members.

PIs involved in research are under pressure to publish in high-impact journals as their career and jobs depend on this. While this is the main goal in any research team, work has to be done safely so that there are no untoward consequences, which would have a detrimental effect on the careers of the PI and team members. Factors that could conflict with the goal of publication and safe performance could include, excessive workload, lack of proper equipment and cumbersome safety rules, among others. In addition to their own research, some PIs are in charge of operating highly complex technology platforms as a core research facility. These platforms are centralized and placed under the charge of the PI most familiar with them, who then provides the service for a fee to other researchers who need to use the technology. PIs who operate such facilities will face the additional goal of the service provision and at least partial cost recovery to operate the core facility.

MATERIALS AND METHODS

Organization where research is undertaken for this thesis

Four biomedical research laboratories were included in this study and fifteen persons working in these four laboratories were invited to participate in this study. The four laboratories were involed in biomedical research in the fields of cancer, metabolic diseases and infectious diseases.

Ethics

Approval from the University's Institutional Review Board to ensure that ethical considerations are in accordance with applicable regulations has been obtained.

Data Collection

This study used the interview method to collect data from the participants. There are three broad categories of interviews that can be conducted to obtain data: structured, semi-structured and unstructured. This study used the one-on-one semi-structured interview method using some key questions and topics (appendix B) to understand and explore the participant's opinions and experiences. This method allows the interviewer to pursue defined ideas while giving the flexibility to diverge and pursue points of interest. It also allows the discovery of information which may be important to the participant, but was not known to the interviewer prior to the interview (Gill, Stewart, Treasure, & Chadwick, 2008). Each response from the participant was used as an opportunity by the interviewer to probe further and to get in-depth information about the participant's views. Participants were asked to draw from their entire biomedical work experience, regardless of country or institution, and not limit their answers to the current laboratory at Duke-NUS. This method was used to uncover the diverse and rich experiences that each of the participants had in a biomedical work setting.

Identification of themes

The aim of this study is to apply Rasmussen's model of boundaries to a biomedical laboratory; therefore, the transcribed data was examined to identify patterns that would fit into the model.

This was done by reviewing the data several times and then coding them such that patterns become discernible by using the following methods (Bernard & Ryan, 2010).

- Repetitions - repeated words in the participant's responses.
- Similarities and differences - in the way the participants respond to the same question or situation.
- Looking for words that occur frequently.
- Repetition in the participant's behavior patterns in response to similar situations.

The coded data was used to identify and characterise the boundaries and the factors that contribute to gradients for the OP to move away from or towards the boundaries. Functionally acceptable performance was defined as performance that did not result in a reportable accident or incident. A reportable accident was an event which caused harm to the worker(s) requiring medical treatment of any kind. A reportable incident was defined as an event that did not cause harm but had the potential to do so.

Procedure

Fifteen participants from the four laboratories were interviewed for about 45 to 60 minutes each between the months of March and June 2017. Participants were interviewed only once, except one participant who on his own accord came back the next day to add to the interview data. All the interviews were electronically recorded with the participant's permission and transcribed into text. Thematic analysis was performed by looking at all the responses and identifying common themes and subthemes (Bernard & Ryan, 2010) (Vaismoradi, Turumen, & Bondas, 2013). The text was then coded into themes based on the response received from the participants. Within each theme, subthemes were identified. All the participants were not asked the exact same questions; therefore, some responses do not total up to 100%, because all the participants may not have provided an answer to every question. On the other hand, some questions, for example the goal conflict of publication failure, had answers from all the participants and the response totaled to 100%. The data is presented as charts, figures, tables and the actual responses from participants in italics within inverted commas.

Demographics of the Participants

The current positions held by the participants ranged from research assistant, post-doctoral fellow and PhD student, with biomedical laboratory experience ranging from 3 to 20 years with an overall average of 9. In biomedical research typically, research assistants are bachelors or master's degree holder requiring approximately 3-8 years of studies respectively. Some workers remain a research assistant and do not join a PhD program, while others may do so immediately after the bachelor's degree or after working as research assistants for a number of years. Post-doctoral fellows are those who work in the laboratory after completion of their PhD programs. It is therefore not easy to correlate the number of years of experience with the position held in the laboratory. Figure 3 provides the breakdown of the demographics.

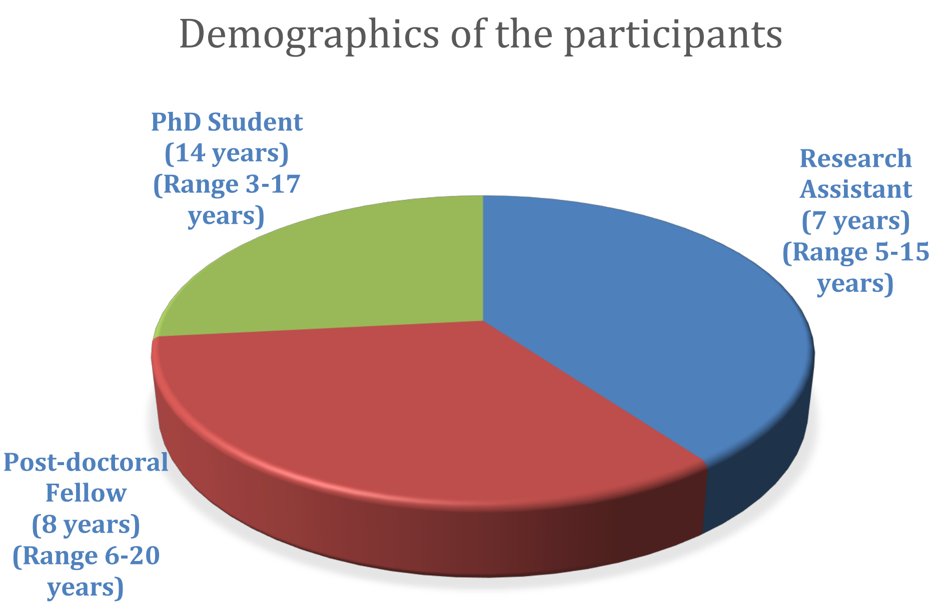

Figure 3: Demographics of participants:
Shows the current positions of the participants and the average (and range) number of years of biomedical experience for each group

RESULTS

In biomedical laboratories, workers have to often face and deal with more than one type of hazard, each requiring completely different set of skills and experience. Therefore, participants were asked about the different types of hazards that they had encountered in their laboratory experience. Five main types of hazard were identified, namely: biological, chemical, radioactive, laboratory animals and animals in the wild. Figure 4 shows the distribution of the number of hazards encountered by the participants and table 1 gives the details of the hazards. All participants encountered biological and chemical hazards. In addition, some laboratories worked with laboratory animals, radioactive materials and collected samples from animals in the wild

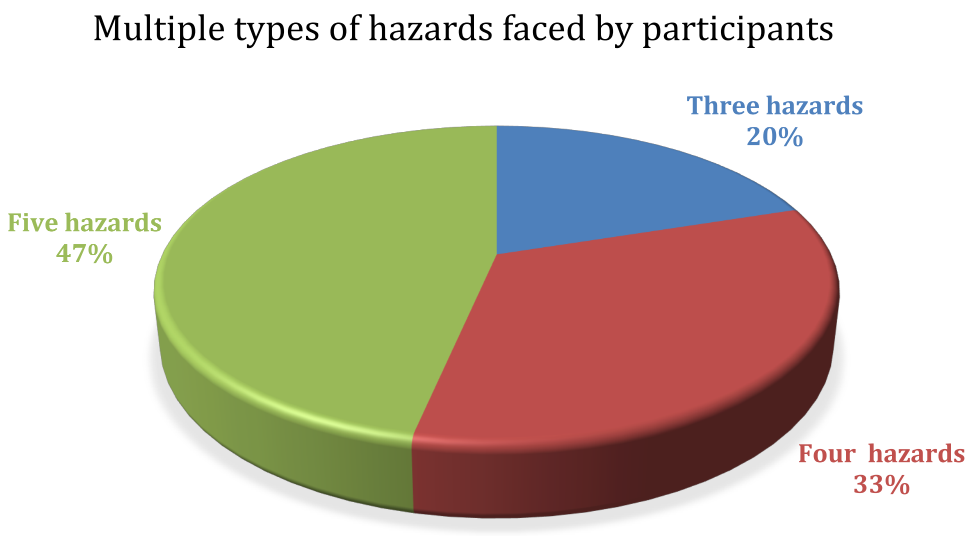

Figure 4: Hazards faced by participants:
Shows the distribution of the number of main hazards faced by the participants.

Hazards faced	Proportion of participants who faced the hazard (%) n=15
Biological hazard Non- infective biological material (not containing microbes that can cause disease in humans or animals) Infective biological material	100 (n=15) 100 (n=15) 67(n=10)
Chemicals	100 (n=15)
Laboratory animals	93(n=14)
Radioactivity	40(n=6)
Wild animals (when dealing with animals in the wild the hazards are completely different from laboratory bred animals.)	27(n=4)

Table 1: Types of hazards faced by participants:
Shows the types of hazards faced by the participants

The different challenges in dealing with the different hazards are evident from one participant's comments:

> *"my work was in different fields, one was radiochemistry/chemistry and the other was more biology and the rules for these two are totally different. Depending on what environment you are working in you have to follow different rules so you have to be conscious about totally different things. So, you can be confused, if for example you have to combine the two in the same day you can be confused and you can transfer your contamination from one lab to the other"*

Accidents encountered

All participants, except two had encountered at least one accident during their time working in a biomedical laboratory. All participants who described an accident said that it happened to themselves or to co-workers. There seemed to be no correlation between the number of years of experience and the number of accidents they encountered (figure 5).

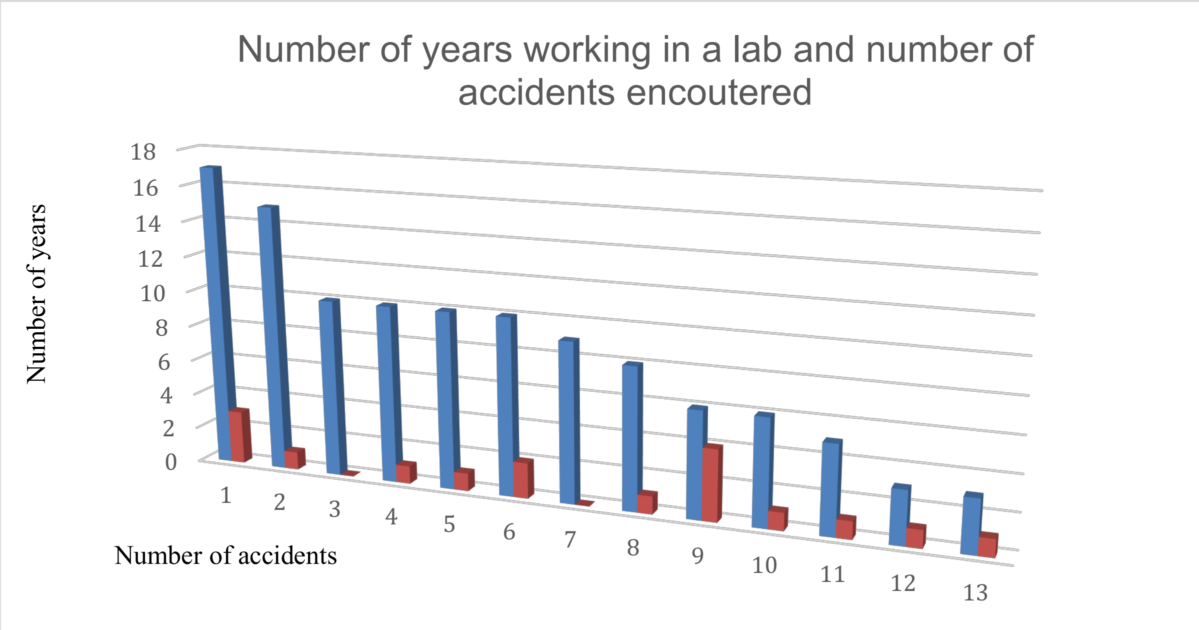

Figure 5: Length of biomedical experience and the number of accidents encountered: Figure shows the number of years working in a biomedical laboratory and the number of accidents they or a colleague encountered.

Plotting of Rasmussen's model of boundaries for a biomedical laboratory

Biomedical research is concerned with generation of new knowledge that can be used to develop new treatment modalities that improve patient care. However, it is not often that discoveries in the laboratory can be directly translated into patient care and one of the ways to measure the success of research teams still remains publications in top scientific journals. Often academic research adopts the publish-or-perish culture. (Hangel & Schmidt-Pfister, 2017). In line with this, failure to publish was a factor that all participants were very concerned about. Publication in turn depended on getting good, consistent and reproducible experimental results. It therefore followed that experimental results were the immediate outcome the participants were concerned with. Scientific output being a key measure of success formed one of the boundaries (scientific output boundary). The second boundary was identified by looking at the challenges faced by the participants to achieve the scientific output. Due to the elusive nature of biomedical research and the inherent difficulty of getting reproducible results, work overload especially when the experiments were time dependent was mentioned by the participants as a key challenge. Reproducible results are critical for publication, which means that the experimental results have to be the same regardless of how many times the experiment is repeated under similar conditions (McNutt, 2014). Work overload being the main challenge formed the second boundary (workload boundary). The last boundary described by Rasmussen is that of functionally acceptable performance (figure 1) the crossing of which is likely to result in an accident, this boundary was therefore termed the safety boundary.

The plotting of the model was done by identifying factors that go towards forming the three (scientific output boundary, workload boundary and safety boundary) boundaries and then identifying factors that contribute to the gradients. Figure 6 shows Rasmussen's model of boundaries plotted for a biomedical laboratory based on the interview information. The results are discussed by devoting one segment to each of the boundaries and related gradient. However, as the description progresses it can be seen that every gradient and resilience building method is used to anticipate and adjust the way they work, in an attempt to avoid all the three boundaries, because crossing any one of them will result in a failure.

The gradients plotted in figure 6 have the effect of moving the OP away from respective boundaries in an attempt to avoid crossing the boundaries. This thesis has looked mainly at the individual worker's responses to the challenges of remaining within the boundaries and their method for coping with them, organizational aspects which were not studied do have a role to play in the entire process. The organization where this research was undertaken is a university medical school where the PIs face pressure from the School to publish, with their career depending on this. Research is typically conducted using funds from competitive research grants, resources like manpower and equipment are obtained through the research funds with the School ensuring that suitable laboratory space is available for the PIs. Gradient 1 is influenced by the organization with gradient 2 being mostly local within the laboratory group. Gradient 3 is most influenced by the organization. In addition to the factors identified (gradient 3) in figure 6, there are several safety initiatives that are at the School-level and compulsory (not drawn in the figure). Examples include, occupational health checks, vaccinations, safety training, mechanism for reporting accidents, access to medical treatment when needed, person protective equipment.

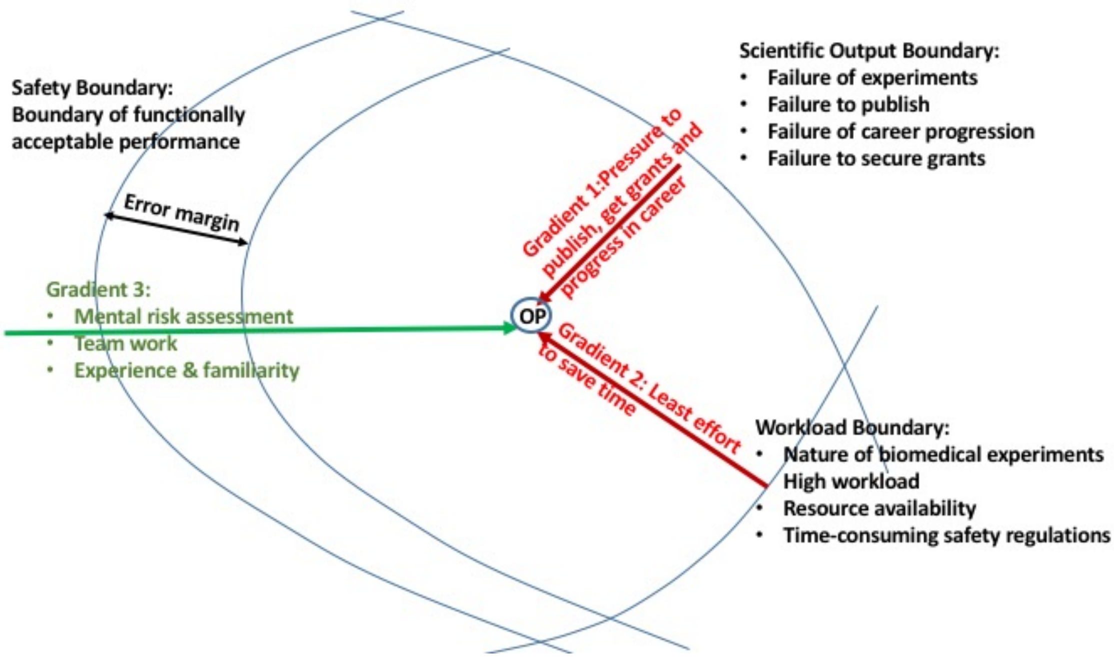

Figure 6: Rasmussen's model of boundaries for a biomedical laboratory:
Shows the factors that go to form the three boundaries and the factors that contribute to the gradients.

Scientific Output Boundary

Factors that go towards forming the scientific output boundary were obtained by asking about the conflicting goals they face in their work. Some participants were not able to understand goal conflict and the question was rephrased to ask about the key work outcomes that they were responsible for. The types of failure the participants were most concerned with were fear of experimental results not being of good quality which in turn was related to not being able to publish and not being able to secure research grants (table 2). In addition, failure of career progression was cited by PhD students and post-doctoral fellows.

Scientific Output Boundary	**Proportion of participants who attributed the factor (%) n=15**
Failure of the experiments	100 (n=15)
Failure to publish	60 (n=9)
Failure of career progression	33 (n=5) Career progression failure was mentioned by all the PhD students and post-doctoral fellow but not by the others.
Failure to secure grants	6 (n=1)

Table 2: Factors contributing to the Scientific Output Boundary:
Table 2 gives the proportion of participants who cited the four types of failure.

Failure of the experiments was a key concern for all the participants and four factors were mentioned that could lead to such a failure as given in figure 7.

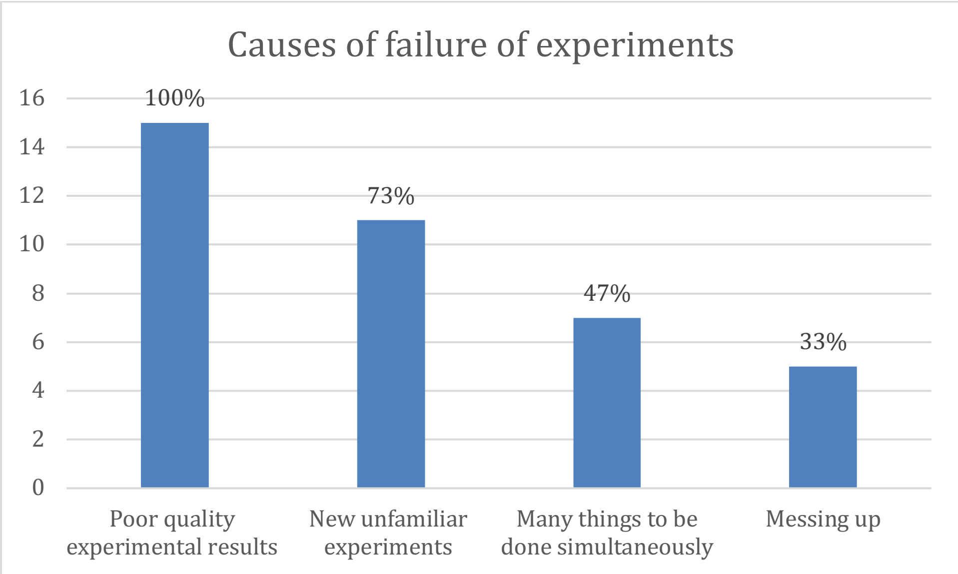

Figure 7: Cause of failure of experiments:
Shows the proportion of participants who mentioned the four factors that could lead to such a failure

Workload boundary

Factors that go towards forming the workload boundary, were obtained by asking about factors that caused excessive workload. Some of the factors cited were long and time sensitive nature of experiments; long time and effort needed to coordinate and plan the experiments; queuing to use equipment, sometimes after office hours; and time-consuming processes in the safety SOP (table 3).

Factors contributing to workload	**Proportion of participants who attributed the factor (%) n=15**
Nature of biomedical experiments	
• Long experiments (as much as 4-6 weeks) that are time sensitive	80 (n=12)
• Long preparation time with multiple people and material needing to be lined up	53 (n=8)
• Critical stages of the experiments and time lines to be met	53 (n=8)
• New experiments/technology	47 (n=7)
• Some experiments are elusive and difficult	7 (n=1)
High Workload	
• Long working hours	73 (n=11)
• Working late due to long experiments or resource queuing time	47 (n=7)
• Multiple simultaneous ongoing projects	20 (n=3)
Resource availability	53 (n=8)
• Queuing to use expensive equipment like laser microscope systems	53 (n=8)
• Precious and scarce samples and reagents	53 (n=8)
Time-consuming safety regulations (SOP)	100 (n=15)

Table 3: Factors contributing to workload:
Shows the details of the factors contributing to the workload boundary

Gradients related to scientific output boundary that could push the OP closer to the safety and workload boundary

Participants were asked about the pressures that could push the OP towards the safety and workload boundary when they were attempting to avoid crossing the scientific output boundary (figure 8). The pressure to be the first to publish was the most important factor.

> *"We have competition…mostly with other groups in the world. Then we have to adjust our priorities because it's about who publishes first and you always worry about people doing work in the same space"*

Competition from other groups doing the same research pushed the workers to work harder and longer hours. In such situations, in order to avoid crossing the workload boundary, they took the path of least effort, which was often in the form of reducing the number of steps in the experimental procedure as well as taking deviations from established safety SOPs (discussed in detail in later sections).

Some participants also described situations where PIs gave the same projects to different members of the team in order to create competition within the team hoping for quicker results. This could lead to unhealthy competition, sabotage and safety risks.

> *"Some PIs give two people the same project to create competition within the group. So, there can be sabotage and unwillingness to share. Its pitting the lab mates against each other. One of the accidents that happened was due to this type of behaviour"*

Publication failure is directly linked to failure of the experiments and participants were under pressure to produce good experimental results:

> "*So, the most important thing for me is that the experiment has to go right. If anything happens and the cells die it's my fault, so I need to make it work. I do a lot of work in the lab for my boss I am on most of the projects and I will do a lot of lab work for him to use in the publications. So, if a PCR* (Polymerase Chain Reaction) *does not work I will ask why is it not working and will try again and again. It's because of me that they are not able to get the publication out. They need that experiment to put in the paper. So, I get affected by that. It's like a failure to me"*

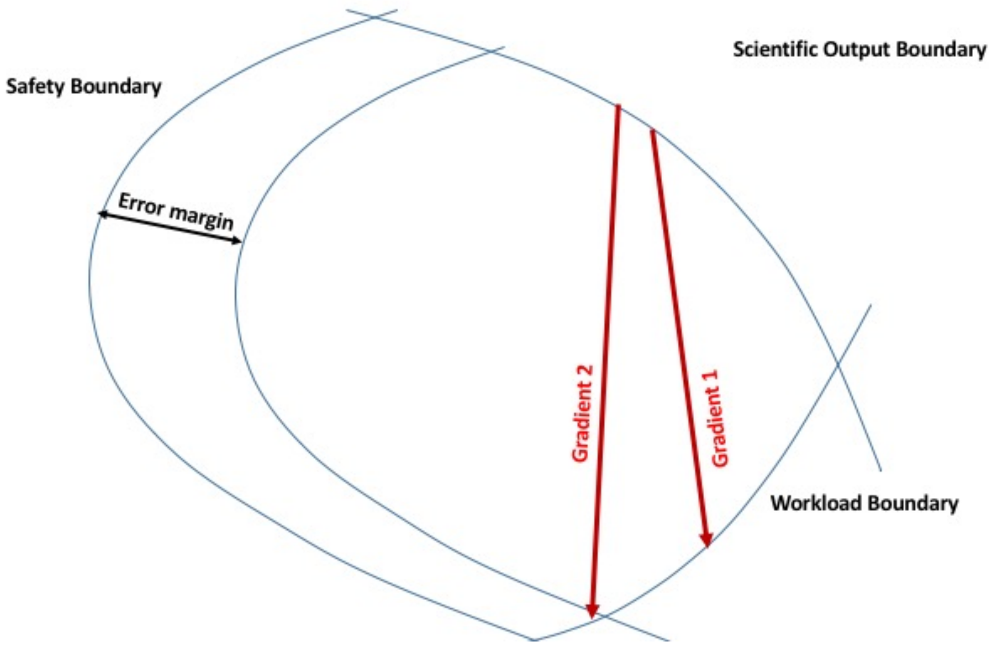

Figure 8: Pressure gradients created while avoiding moving past the scientific output boundary:
Scientific output being most crucial for the laboratories, they would avoid moving past this boundary by increasing their workload by working longer hours to get the desired scientific output (gradient 1). If competition becomes unhealthy as described by one participant the risk of crossing the workload and safety boundary may increase manyfold (gradient 2).

Gradients related to workload boundary that could push the operating point towards the safety and scientific output boundary (figure 9)

The tedious nature of biomedical experiments was cited as a factor by most participants.

> *"For me certainly it's the multiple projects in different directions, each very different. The risks are different so you have to juggle with a lot of balls in the air at the same time. Again, you have to prepare yourself days before, it's a choreography because you are playing with time and it's very critical that you are very well prepared and planned with step by step schedule. It's planning, planning, planning, before putting your hands on anything"*

One participant explained that during the critical and exploratory stages they have to be very attentive to make sure that all the planning is not wasted and you get the maximum out of the experiments.

> "*you always want to get as much as possible in the least amount of time, you may have a very important five-hour experiment and you are working on this model a lot and you are planning this experiment for a long time. In this five hours, you want to get the maximum results and get the most out of it, you have to cram a lot into the window of opportunity"*

Some experiments may need to use core equipment that are only available through a booking system, because they are expensive systems and every laboratory would not be able to buy and operate their own. This can cause them to have long waiting times. One participant explained that they had to use a machine at the hospital so they had to wait until the routine patient work was complete before they could use the machine.

> "*I had to wait for a machine in the hospital, sometimes I have to wait till midnight or 1-2 AM, we just wait"*

Participants also said that some reagents and experimental animals were expensive and some samples were precious and they had only small amounts to work with. One participant explained that collecting samples (blood) from a small mouse came with experience and cannot be written down.

> *"there are things that can compromise samples that you are collecting from the animals… This comes with experience, with animals they can be unpredictable and you cannot put (*the procedure*) on paper, so it has to be at the moment"*

All participants felt that fully following the SOPs was time consuming (figure 9). They felt that the SOPs were sometimes not practical and probably written by those who did not know how laboratories worked.

> "*people who make the rules should understand how a lab works, when something happens they impose some rules that are very impractical, they don't know how a lab works and they will think it's just one step why can't you do it. It will affect all our day to day work and procedures. I think SOP is very useful, of course it will minimize the risk but a lot of things are redundant and troublesome*"

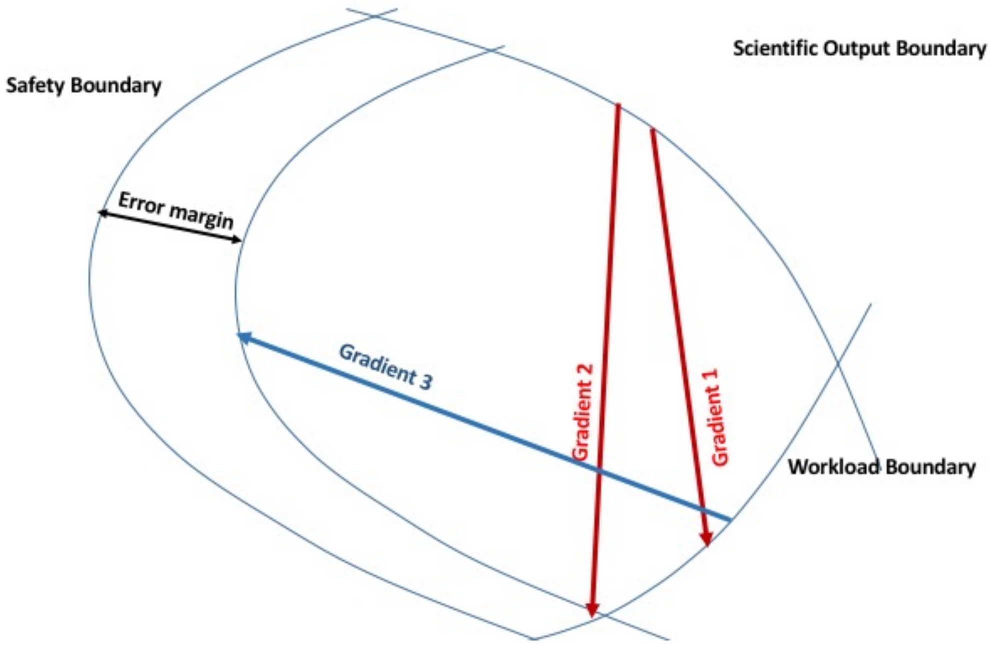

Figure 9: Pressure gradients created while avoiding moving past the workload boundary:
Pressure to get scientific output creates higher workload for the workers and they work longer and harder (gradient 1 and 2). In order to control the workload and avoid moving past the workload boundary they choose the path of least effort by deviating from time-consuming SOPs (gradient 3). While pressure to get scientific output is the main factor that causes increase in workload, within that pressure there are several factors that could add to increase in workload, these are explained in table 3.

Safety Boundary

The participants described several mechanisms that they used to prevent crossing the scientific output and workload boundaries. Many of the mechanisms came naturally and they did not stop to think which boundary was being avoided and most of the time multiple boundaries were avoided with that one mechanism (figure 10). The School manages safety through the establishment of OHSMS, one component in such systems is standardization. Since each laboratory encounters different risks, implementation of standardized risk control measures is not always practical and does not allow local variability. The SOPs are usually developed at a much higher level in the organization and often are not practical in performing the daily work. Another consideration in the field of biomedical research is that new developments and challenges occur frequently and SOPs and regulations to deal with them often lag behind (Faunce, 2007). In such situations the workers carry on with the work and often deviate from SOPs to meet the new challenges. Deviation from such SOPs are common in the laboratories and the emphasis on deviations from SOP in this thesis was aimed at understanding what methods of assessments the participants used to assess the risk in such deviations. One often used method was to take the path of least effort in the form of deviations from established SOPs. Since such deviations could push the OP closer to the safety boundary it may result in an accident or incident. The risk of such deviation with improper assessment of the risk could lead to crossing of the safety boundary and hence was examined in this study.

Each of the laboratories included in this project were different in the type of work they did and the types of hazards they faced and they had SOPs that were both organization-wide as well as laboratory-specific that they had to follow at all times. The one standardized method of finding indicators that the OP was moving towards the safety boundary was therefore, deviation from SOP. Therefore, in order to get information about what makes them deviate from SOPs, the participants were first asked to give their opinions about the applicability of the SOPs to their daily work procedures (table 4).

All participants said that the SOPs were not always practical nor commensurate with the risk and they would deviate from it if they felt it was safe to do so based on their mental risk assessment. All participants also said that as they became more familiar and experienced in the procedures they would omit some steps that they felt was not necessary.

> "*we have to do identify what is risky for a new person and this may not be risky for someone working on it for a long time. It is like market design, where to make a better design you consult*

the consumer, you don't just make a product. This is similar to that. When we design rules, we should consult the consumer of those rules and not just make them"

Some participants felt that SOPs were very long and not many people would read it, making them not so useful.

"To be honest the only people who really read are the one who write it….. as a junior, we will learn through experience and mentoring. When I was a junior I questioned my senior a lot. It is important to keep this open mentality"

Opinion about SOPs **n=15**	**Yes**	**No**	**Not Sure**
SOP are useful	60% (n=9)		40% (n=6)
SOPs should be broad and not too detailed	73% (n=11)	7% (n=1)	20% (n=3)
Local variability should be allowed	73% (n=11)	13% (n=2)	13% (n=2)
SOPs should be practical and commensurate with the risk	100% (n=15)		
We learn more from mentors and colleagues than from SOP	60% (n=9)		40% (n=6)
Do SOPs prevent accident?	67% (n=10)	13% (n=2)	20% (n=3)
Do you deviate from SOP based on mental risk assessment and familiarity	100% (n=15)		

Table 4: Participant's opinion about SOPs:
Table 4 gives the participant's opinion about SOPs and their application

Reasons for Deviating from SOP

The participants were asked what caused them to deviate from the SOPs, the most common reason for deviating from the SOP is to ensure that the experiment was not jeopardized, especially in time sensitive experiments with precious samples and reagents (table 5). In this case the worker is trying to stay away from all three boundaries as explained by one participant:

"If it is the final result, then you are more stressed depending on how thirsty you are for this result… Also, it has to do with planning experiments in terms of cost, you cannot just keep on

buying animals or reagents so you have to be conscious of the tools you have and how precious they are. The more precious they are the more stressed you are because you don't want to use it up wastefully. You cannot just play with that so this is critical if you have only 500 mg of a protein you have to be mindful and cannot make too many trials"

Another reason for deviating from SOP is the incentive to publish in top journals which will help them to advance in their career or graduate.

"Usually when new work we will have a hypothesis and sometimes you want the hypothesis to be true that way you can achieve your goal (career) faster. Sometimes you want it to be fast and you will cut corners"

Reasons for deviating from SOP- using path of least effort	**Gradients drawn in figure 10**	**Proportion of participants who mentioned the reason (%) n=15**	**Boundary being avoided**
Results are needed urgently	1	73(n=11)	All three boundaries
Time sensitiveness, when a lot has to be done within a short time for example: • sample collection at 0,5,10 minutes. • Work with radioactive isotopes with short half life	2	60(n=9)	Scientific output boundary
Increased workload	3	53(n=8)	Workload boundary
Convenience	4	53(n=8)	Workload boundary
Tiredness	5	33(n=5)	Workload boundary
We learn from seniors and follow their method which omits certain steps	6	27(n=4)	Scientific output and workload boundary
Samples and reagents are precious and any loss would jeopardize the experiment	7	20(n=3)	Scientific output boundary
Ignorance of the risks and steps that need to be followed	8	20(n=3)	Workload boundary
Resource availability like equipment queuing which takes up our time	9	13(n=2)	Workload boundary

Table 5: Reasons for deviating from SOP:
Shows the reason for deviating from SOP and which boundary was being avoided by the deviation. Gradients 1-9 are drawn in figure 10.

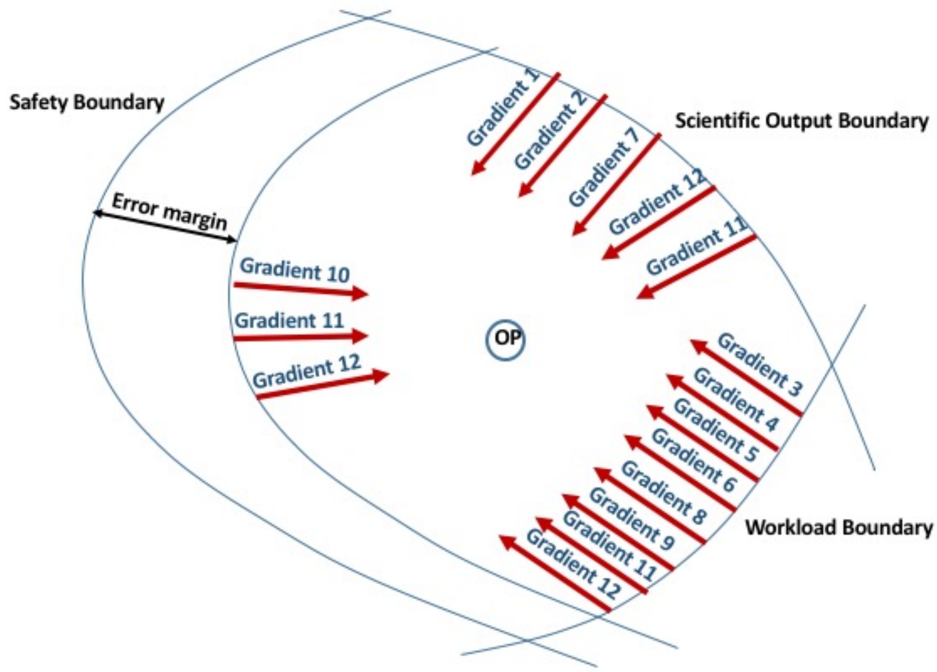

Figure 10: Gradients that can affect the OP:
Figure 10 shows the gradients related to the boundaries that push the OP closer to the other two boundaries. As can be seen from table 5, the participants deviated from the SOPs to avoid all three boundaries and remain within the bounded space. They used resilience building methods (see Resilience Building Methods section) to avoid moving past all the boundaries. The process is dynamic and any one method is used to avoid one, two or all three boundaries with constant change and movement of the OP. The gradients labeled 1-9 are described in table 5 and gradients labeled 10-12 are described in table 6.

Examples of short cuts taken and the boundary that is being avoided by the participants

Example 1: Avoiding scientific output and workload boundary

One example of deviation from SOP discussed by the participants is the use of the fume hood, which is a special ventilated cabinet designed to limit exposure to hazard (Walters & James, 2011). Fume hoods are located in certain areas and the SOP says that **all** volatile chemicals should be handled inside the fume hoods. However, participants do a quick mental risk assessment to evaluate the risk and then if they consider it to be low, they don't take the trouble to walk to the fume hood but do the work on the laboratory bench.

> *"we prepare chemicals like formaldehyde or chloroform on the bench because we don't want to walk to the fume hood. I know chloroform is worse than formaldehyde but it is for short exposure. Sometimes we have to prepare and spin samples and has to be done within a certain*

time. So, I open, take out and recap the bottle quickly. I am paying attention to make sure that the exposure is really short and no one else is nearby".
"If you are handling minor things you will skip some steps, we do risk assessment and the likelihood in our mind without even thinking about it. Let's say we switch on the plug (electric) we don't think about it"

Example 2: Avoiding scientific output and workload boundary

The SOP says that a secondary container is required for transporting **all** liquids. Participants said that they would do a quick assessment and if the liquid was innocuous they would omit the secondary container, even though the SOP says it needs to be done:

"when we transport chemicals, there is need to use secondary container, if I am just transporting some cells in a buffer I will not use secondary container because I think it is not safer and I need to get things done fast. If I go to another floor I will use it. If it is radio- tagged I will also use secondary container. So, in my mind I do the risk assessment without even realizing it"

Example 3: Avoiding scientific output boundary

Biological samples are stored in large liquid nitrogen tanks because of its extremely low temperature of -196^{o} C. SOP says that when taking samples out of liquid nitrogen tanks workers must wear cold resistant cryogenic gloves to prevent frost bite. Cryogenic gloves are thick and heavy and do not give the dexterity required to handle the small vial of extremely precious biological material (figure 11). The participants do not wear the cryogenic gloves and instead allow the liquid nitrogen to drain off before handling the vial so that nitrogen in the liquid state does not touch their hands.

"Another example is liquid nitrogen, we use it to store cells sometimes when we handle these, there are lot of PPE (personal protective equipment) *requirements, some are bulky, you don't really have the dexterity, so we do without the PPE. Depending on how experienced you are, you can be safe. If the vial fell into the tank, then I will know the danger is higher and we will wear the cryogenic gloves or use tongs, so we do a mental risk assessment. When the rules are hindering we don't follow unless based on our own experience or the seniors telling us and we feel that it agrees with the safety precaution then we will do it. But if we can get away and it is a hindrance we cut corners"*

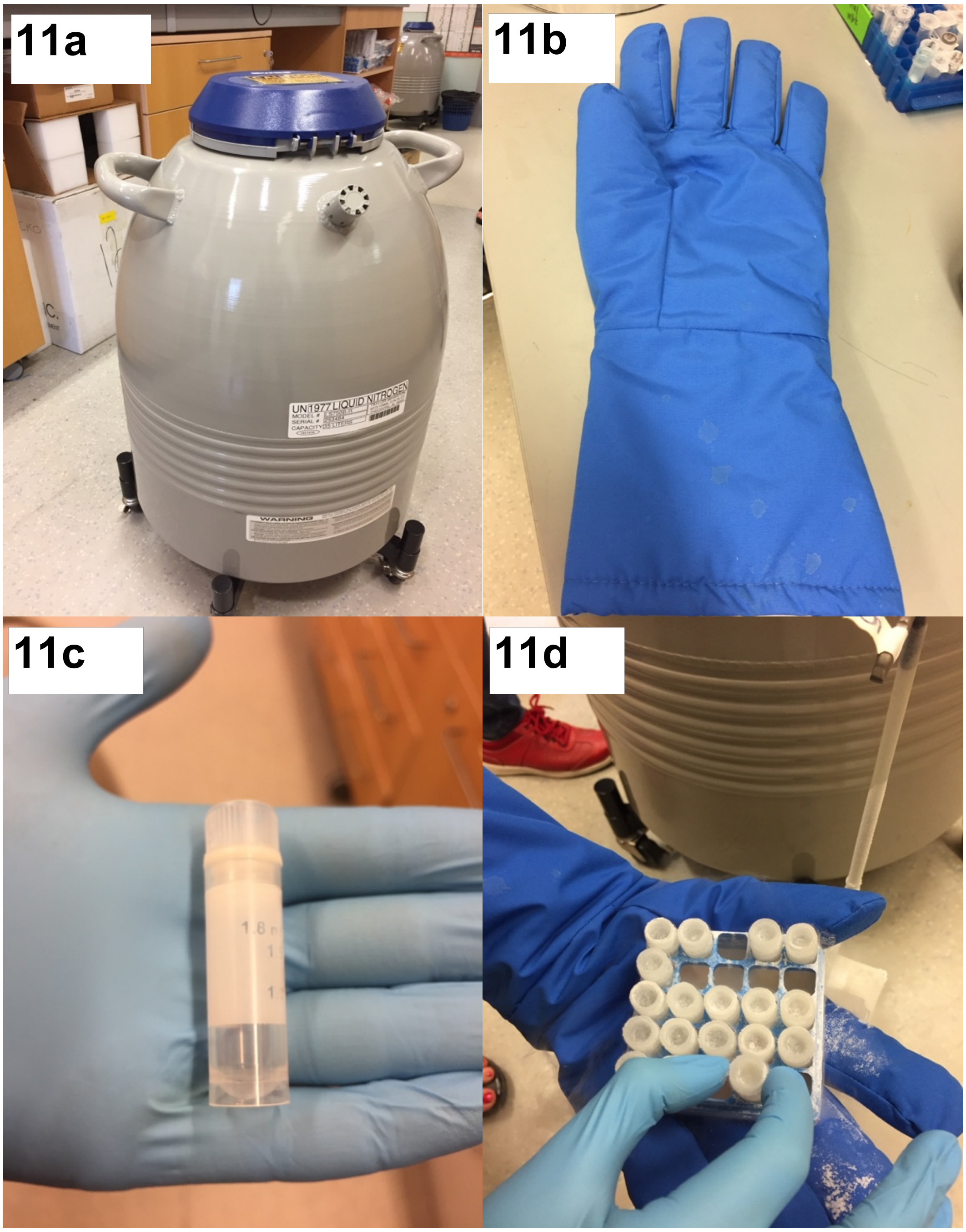

Figure 11: Examples of deviation from SOP:
Shows a liquid nitrogen tank (11a) which is used to store biological material for long term. 11b shows the thick cryogenic gloves that needs to be worn according to the SOP to take any samples out of the liquid nitrogen. The samples, which are extremely precious and may be the result of several decades of research work, are in a small vial which is shown in 11c. 11d shows how the workers used nitrile gloves (deviation from SOP) to allow dexterity so that they do not drop the vial of biological material.

In these above examples the participants are deviating from the SOP after they perform a quick mental risk assessment and deciding that in order to perform the work successfully, quickly and with minimal effort the risk taken is minimal.

Resilience Building Methods

The challenge in the laboratory is to ensure that experiments produce the desired results, while ensuring that no accident or work overload occurs. Workload in a biomedical laboratory consists of periods of intense work and periods of little work. Work is intense during some experiments which require a lot of coordination and multiple interventions at regular intervals and relaxed at times when such experiments are not ongoing. Participants were showed the Rasmussen model of boundaries and asked how they ensured that the OP was within the boundaries. The methods described were: a) performing mental risk assessment before they did any task; b) team work where they looked out for each other; and c) experience and familiarity which came through mentoring and actually performing the experiments (table 6).

Methods	Gradients drawn in figure 10	Proportion of participants who mentioned the method (%) n=15	Boundary being avoided
Mental safety risk assessment	10	100 (n=15)	Safety boundary
Team work	11	100 (n=15)	All three boundaries
Experience and familiarity, which is achieved by the following:	12		Safety and scientific output boundary
• Mentoring by seniors		100 (n=15)	
• On the job learning		100 (n=15)	
• Learning from accidents experienced by participant or colleagues		100 (n=15)	
• Sharing of experience and expertise through culture of open communication		100 (n=15)	
• Learning from safety information sheets and internet		53 (n=8)	

Table 6: Resilience building methods:
Shows the resilience building methods used by the participants and the boundaries they were aimed at avoiding

Mental Risk Assessment

All participants performed a mental risk assessment before deciding to deviate from a process in the SOP.

> *"I use the ranking system to assess the risk in my mind"*

Five participants did not realise that they were performing a mental risk assessment until it was pointed out at the interview.

Familiarity with the procedures and experience in doing them were also factors that made them deviate from SOP. Participants said that when they first learned a technique or procedure they would do it slowly and follow all the steps. Once they got good at it and had the knowledge of where the pitfalls were, they would deviate from SOP.

> *"In my mind, I know which risk I can and cannot take. Like double gloves I will decide when I want to wear and when not because I will lose dexterity if I wear two gloves"*
> *"..but after doing these things you tend to know what to look out for, what to be careful about as you become more proficient"*
> *"Yes, I am aware of it* (deviating from SOP) *only when I am very familiar and very experienced with what I am doing, and then I will cut out some steps, but when I am at the beginning of a new experiment that I am not familiar with then no, I will follow everything by the book. But the more I get experienced the more I can optimize my routine and eliminate some steps that I have seen before that are not necessary"*

Team Work

The nature of biomedical research is such that many things [animals at precise weights and ages, sample collection, equipment availability, reagents with extremely short shelf-life (sometimes a few minutes) etc.], have to be lined up before work can commence and when everything is lined up making mistakes will mean starting all over again and losing time, money and precious samples.

> *"I work with nocturnal animals so you have to operate at night. It's about how you balance your sleep awake cycle and I think fatigue is the biggest one because that's where accidents happen. It's not how you push the boundaries it's that we have to work at night because that's when these animals are active. So, we have to be able to watch out for each other"*

Laboratory workers work in teams with a more experienced person leading the rest. The projects are divided among the teams and the workers have independence and responsibility to plan the work to ensure that it goes smoothly and they coordinate within their team to plan the work.

> "*trust of the PI and lab mates* (is important), *not micromanaging, micromanaging is very stressful, after the initial discussion leave us to do the work and we know that you* (the PI) *are there for any trouble shooting for us. Trust is most important"*

Participants explained that when they perform complex work, they plan for days ahead before the work can commence.

> "*Multiple things have to be lined up, like a drama production with each player knowing what to do and others stepping in if one is unable to perform the task"*
> *"it is designed very precisely, you have a tight schedule. You cannot afford to make a mistake"*
> *"You definitely have to plan well, the way I see it it's like a choreography it has to be"*

One participant described that they watch out for each other and often have both formal and informal chit-chats to plan the work.

> *"Experiments with short half-life radioisotopes, taking multiple samples I will plan ahead. I will schedule even in my mind I will think about who is in charge of what at least three people are involved and I will plan like a drama production about who does what in what sequence. A lot of communication and we will sit together and work the schedule. If someone can't do we will swap the work"*

They worked in teams and watched over each other to:

> *"catch the balls so that none fell to the ground"*

When a colleague appeared to be overworked they asked the colleague to go home to rest and took over his tasks. Later they asked the colleague to discuss with the PI to redistribute the workload.

> *"We asked the colleague to talk to PI and to get others to share the load. Some people don't care what you do and don't bother to speak about it. Like-minded (the participant was talking about helpful and open-minded) people in a group is good for open communication culture"*

Participants said that things went well they all would benefit from that and share the success, so they planned such that they can divide the work load among each other.

> *"helps so you reduce each person's workload to a doable amount"*

Sometimes they would make sacrifices to reduce the higher risk work (in this case taking blood from animals) and continue with the lower risk procedures, when they were tired.

> *"our team has a very good synergy if some of us are very tired, we will say let's just process some of the samples. For example, if it is 2 am we will decide to stop blood taking and maybe we do swabs, so rather than take the risk and achieve the results we reduce the work"*

Sometimes if they were not so experienced in the procedure they would ask a more experienced person to do it for them.

> *"If I am tired or unfamiliar with something then I will get someone experienced to do it with me. Two persons is better than one"*

When they did complex, tedious and risky work they would build in redundancies in the form of asking colleagues to standby in case of any problems or asking colleagues to watch over them to see if any issues are developing that the one performing the work is not able to see.

> *"… sometimes what happens is that you get this deer in a headlights kind of situation and that is the worst probably that could ever happen when dealing with novel stimuli* (new material that they have not handled before) *problem you are just staring at it and don't know what*

to do, in this situation the worker could put themselves at risk so the co-workers watch out and quickly move in to avert the situation"

One participant described what happened when working with radioactivity as follows:

> *"Once we had to store this really hot isotope, so it was delivered and we were not fully prepared. I tried to get shielding* (barrier made of special material used to protect workers from radiation exposure) *from all other places to come up with this DIY* (do-it-yourself) *contraption of piling lots and lots of shielding around and going around it with a survey meter* (to detect radioactivity outside the shielding) *but even then, it wasn't a structured thing it just came together at that time"*

Experience and familiarity

Participants felt that the best way to learn was through a good mentor and by doing the work themselves. All participants very strongly felt that mistakes, accidents and incidents whether it happened to themselves or colleagues were the best teacher. All participants said that when they learned a new procedure or used new material they would be very careful and follow the SOP. Once they became familiar they would deviate from the SOP based on mental risk assessment and their familiarity with the procedure.

> "*I optimize my routine and eliminate some steps that I have seen before that are not necessary*"

> *"In the beginning, we need to do more carefully. And will take longer time. Once you are fluent in the work then you can decide not to wear some PPE. In my lab before you do something even if you are experienced we have to learn from seniors how to do it and operate machinery etc. you talk to the person about what you can do what corners you can cut etc"*

One participant said that before they attempt work that is risky, like infective agents, they practice the procedures without the virus but by going through the entire procedure and only do the real work when they are very familiar with the procedure. This helps to stay away from both the scientific output and the safety boundaries, because they do not want to use up the precious samples and also do not want to have an accident.

> "*We are now rescuing recombinant viruses that is a new thing for our lab, we did a fake rescue several times, there is no virus we practice without the risk"*

All participants said that they learned from the seniors; the seniors play a key role in passing on knowledge about the procedure and the safety aspects. Only 20 % relied on the SOPs to learn the safety aspects of the work and about half of them got additional information from the internet or safety information sheets. One participant said that when as juniors they learn from a good senior they also learn how to be good mentors when it is their turn.

"What I am now is because of this one person in the lab who I learned from, when I mentor I always encourage my juniors to question me"

"It's the PI and senior people in the lab who have to nurture the safety culture and be examples"
"I think my lab culture is very open we share and we don't judge. It really depends on the lab culture, my bosses mentor and groom us and we are not afraid to approach them. We can tell them that we made a mistake the experiment failed or that I had an accident. We discuss and revise SOP if needed. We do make small mistakes. One time someone put a bacterial flask in the shaker incubator. Even though it was the right size it was a little lose and flew out of the incubator our colleague told us what happened and everyone was aware of it. So, we use the fatter flask even though it's the same volume. Yesterday someone wanted to do it and was afraid and we all said use the fatter flask and we all went to look for the fatter one together. We stood there and put paper towels and made it fit and stood there for like half an hour to make sure that it doesn't come out and then we went back to check. My lab, we are very close we watch out for one another, but some other labs are not like this they are very competitive. My lab is amazing, we communicate and share and admit our mistakes"

Safety Training

Since familiarity and experience was an important factor that helped them to avoid crossing the boundaries, participants were asked what was the best way to teach them to work safely. All participants said that they learned from their seniors who mentored them and told them about risk and safety in each step of the procedure and what to look out for. All participants also said that they learned from accidents or incidents encountered by themselves or colleagues and that mistakes were the best teacher (table 7). One participant felt that open communication and a no blame culture could go a long way in learning from mistakes

"A mistake is always considered as a personal failure, but I appreciate a more open policy with no blame and no consequences. No one does it on purpose if something goes wrong do you discuss it or do you cover it up?"

How do you learn techniques and safety	Proportion of participants who mentioned the method (%) n=15
From our seniors	100 (n=15)
Through mistakes/accidents and incidents (ours and other colleagues)	100 (n=15)
Accidents or incidents that happened to people we know	73 (n=11)
Seniors telling us about their accidents and incidents	60 (n=9)
Other colleagues pointing out a safety issue	53 (n=8)
Internet and pamphlets that come with kits and regents	47 (n=7)
Standard operating procedure	20* (n=3)
Safety campaigns and posters	7** (n=1)

Table 7: Methods of learning experimental techniques and safety:

Shows the different methods used to learn experimental techniques and safety.

* three participants said that SOPs were a source of safety information and one (not included in the table above) said that SOPs and regulations did not provide usable safety information, he said

> *"it's like market design, you have to first know what the consumer needs and design the product according to that, but SOPs do not seem to take into consideration what the consumer (us) really can use"*

**Only one participant said that safety campaigns and poster may have some benefit.

> *"it will catch your eye you may not pay too much attention I don't know if subconsciously it has an effect. May be in the long run they can be useful you don't see the immediate effect. I would keep them it may not have too much effect but it does no harm so it's useful. It still sends a message"*

All participants said that an accident was the best teacher. They said that once they encountered such an event they would be very careful when dealing with a similar procedure.

> *"personal experience is the best teacher for you I think last time we can weigh the chemicals outside the fume hood. There was a major incident I was choked by the SDS* (commonly used chemical). *I followed the seniors, I only realized when it happened to me and then I read about it. I knew the risk but I didn't think about it and its not life threatening. So, I was willing to take the risk at that time now I never repeat it and I do in the fume hood"*

Participants felt that SOPs were long and difficult to read, most of them did not read it and they just learned from the senior who was mentoring them. Some participants felt that videos and visual material would be more useful for training.

> *"The hands-on training from an experience person will have more immediate effect. An accident is the best teacher if they have faced the situation and without the real thing it is difficult to get across that message even in a mock up session"*

In one of the participants' previous work place, they used a lot of scenario training which the participant found very useful.

> *"We had a senior safety person who gave us scenarios, as we were sitting in a class room with 10 people we had clickers and a,b,c,d multiple choice questions. For example, the scenario was your colleague was bitten by an experimental animal chose an answer. Without blame, you get the feedback on what people would do, the learning effect was the best. You can make up scenarios there may be more than one way to react, you see how the audience reacts and deals with it"*
> *"Even if you read all these danger and red lights if you don't see it in practice, for me at least, you will not realize what this danger means. Having had an experience you are much more conscious of what the dangers are and what you are handling"*

When asked how safety training could be improved, participants said that mental risk assessment methods should be taught and this would be very useful.

> *"you can teach them how to separate the dangerous work because you can't be careful all the time. Explanation is very important, they should understand the risk and why they should do it this particular way. Logical people will follow. Like all sharps must go in the sharps container is non-negotiable. Certain things can be variable. Like a mouse that may bite, people will let go no matter what the SOP says. For animal work, I have a very good mentor who teaches me animal work and is very willing to share his skills and knowledge. Skill is very important. Training and experience also. The mindset to go home safely is very important, tell them their loved one is at home"*

Participants felt that explanation is very important; if a risk and the control measure was explained to them they would be more able to accept it. If mentors explained not only the experimental step but also the risk of each step, it would be easier to remember.

"The logic seems clearer when you talk informally, when you say why we should do things this way. It sticks in you better. An accident has best effect on me when I am pressed for time, when I am not pressed for time I will be a lot more careful".
"If you train someone, it is your responsibility to make sure that they understand safety".
"small group discussion will be hugely beneficial, but I am very skeptical that people will not be willing to expose their frailties or errors. I think if you put together a compilation of seniors who are willing to give that to the juniors. Just bringing people together may not work because people never want others to question them like undermining their authority. I let my staff know when something happened to me. Look this happened let's make sure it doesn't happen again. I think we have to watch video and power point if after that the junior and senior spent 15-20 mins talking about what they learned then we can have an idea of retention, we can have a tick box that senior and junior met after that and what did they get out of it, you can get feedback on what was good in your presentation and what was not. you still need a few senior people to open up, otherwise they are going to sit around the table"

DISCUSSION

In 1997, Rasmussen asked a very basic question: "Do we actually have adequate models of accident causation in the present dynamic society?" (Rasmussen, 1997, p.183). In trying to determine a good model to study accident causation, he explained that while stable systems could be modelled by decomposition into structural elements, dynamic systems would have to take into consideration changing demands, risks and competition in the workplace. In other words, while traditionally safety was managed by laws, rules and SOPs, these were not adequate in a dynamic workplace. Such rules and SOPs could not be followed to the letter even in highly regulated industries like nuclear power plant operations and workers would realise that they have degrees of freedom to perform their tasks. As workers get more experienced in the tasks, they will have more choices in performing the tasks based on practice and know-how and they will exercise these choices based on the workplace demands (Rasmussen & Svedung, 2000).

In order to model this freedom of choice that workers have and exercise, Rasmussen came up with a model of boundaries with the operating point falling within the space bound by the boundaries (figure 1). This project used interview data from fifteen biomedical laboratory workers to plot this model of boundaries for a university biomedical laboratory. Rasmussen described the three boundaries as economic failure, unacceptable workload and functionally acceptable performance, the corresponding boundaries in a biomedical laboratory based on the results of this study are scientific output boundary, workload boundary and safety boundary (figure 6). In an attempt to avoid crossing any of the boundaries the workers would take certain measures that could move the operating point closer to another boundary. These are termed gradients and are also drawn in figures 8, 9 and 10.

Biomedical laboratories are under extreme pressure to be the first to publish in high impact journals and their entire career and existence depends on this (Anderson, Ronning, De Vries, & Martinson, 2007). This was reflected in the interview responses from the participants, all of whom were most concerned with getting good experimental results, this in turn was related to publication. The nature of biomedical research is in itself tedious because of inherent uncertainties and elusiveness in obtaining reproducible results (Gori, 2014). Therefore, in order to avoid crossing the scientific output boundary, participants were often working close to the other two boundaries. They were aware of pitfalls pertaining to both overwork and safety and were using the following methods to remain within the boundaries:

a. Deviating from SOP in order to follow the path of least effort;

b. Working in teams and planning and coordinating the work processes well in advance; and
c. Using their experience and familiarity with the processes which was in turn was developed through mentoring, on the job training and learning from accidents and incidents.

The OP is in a constant state of movement and any one gradient to avoid crossing a particular boundary, say workload will also help to avoid crossing another boundary say scientific output. This can be seen in figure 10 where the same gradient for example team work can be used to avoid crossing both the scientific output and the workload boundary. In addition, it will also avoid crossing the safety boundary because the workers “watch out” for each other. By working in teams, they are ensuring that the experimental results are of good quality, they are not doing anything unsafe and they are dividing the work among themselves such that the amount of work is “doable”.

These methods bring to mind the concept of resilience, which is the ability to anticipate and manage unexpected or expected demands in the workplace (Woods, 2006). The unexpected demand can be an accident, changing pressure to produce results, increase in workload or other disruptions all of which require the workers to be adept at anticipating and responding to these demands. The idea of applying the Rasmussen’s model of boundaries to study resilience is not new and has been attempted by others. A study on the Dutch railways has attempted to find quantifiable parameters to study resilience (Siegel & Schraagen, 2014) using the model of boundaries. The authors use the angle of the slope when the model is viewed from above to measure resilience, with a small slope denoting brittleness and a large one resilience. Such measurements are not easy to devise and this thesis has not attempted to do that, but to simply understand the factors that form the boundaries and gradients and the resilience building methods employed by the workers. This is similar to another paper that has also applied the model of boundaries to healthcare, in which the authors simply point out that knowing the boundaries and the location of the operating point, for both organizations and individuals, is essential to remain resilient and avoid failure (Nemeth et al., 2008).

The OHSMS method of managing safety, which is the current practice in Duke-NUS Medical School, includes prescriptive predefined elements consisting of processes, legal compliance and SOPs, the success of which is predominantly measured by the number of accidents. This follows the concept of safety I, which is avoiding what goes wrong as opposed to safety II which looks at what goes right (Hollnagel, 2013). The results of this study show that workers are already employing methods of resilience to avoid crossing any of the boundaries while at the same time working close to the safety and workload boundaries in an attempt to remain productive and avoid crossing the scientific output boundary. The workers not only are aware that they are working close to the boundaries they also use methods of resilience to remain mindful of the boundaries and if we follow the concept of safety II and strengthen these methods we will be able to further improve their performance. In 2016, there were no major injuries and the rate of minor injuries was very low when plotted against the man hours of work done in the School (Vijayan, 2017). Figure 12 shows the rate of minor injuries and it can be seen that 99.9 % of the time things went right. The results of this project provide valuable information that can be used to apply safety II concepts of supporting the workers in what they do right thereby strengthening the resilience building methods.

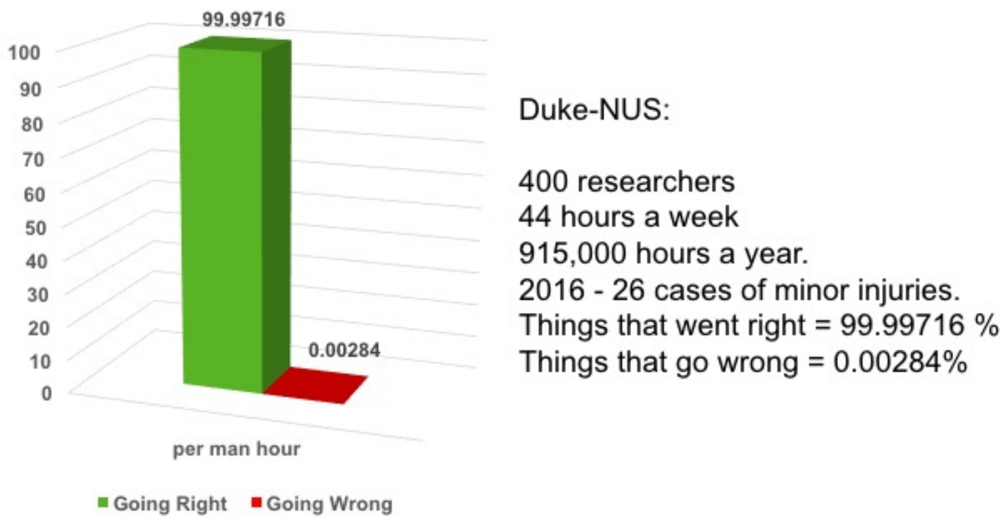

Figure 12: Injury statistics:
Shows the injury per hour of work in the School for 2016.

The complete dependence on prescriptive methods, for example a detailed written SOP, does not take into account the fact that not everything can be known. Such SOPs are not useful because it is not possible to write everything that could possibly happen while performing that procedure into the SOP without it becoming very lengthy and impossible to read. A typical example is what one participant said about working with animals which comes with experience and one cannot put the procedure down on paper. In order to deal with the unexpected, the only resource available is the workers themselves and the view that expert operators are a source of reliability (Lay, Branlat, & Woods, 2015). The authors explain this shift in the practice of safety by using five principles of resilience, a) variability; b) reliability of expert operators; c) complex systems need a system view, d) it is necessary to understand normal work; and e) focus on creating safety. While the authors discussed resilience in the practice of safety in this article, the results of this study show that the practice of resilience also addresses other failures like productivity and workload.

Another aspect that the participants brought up is unhealthy internal competition that could lead to sabotage and the participant said that is was the cause of an accident that the participant had encountered. While this is not specifically addressed in Rasmussen's model it is likely that the resilience building methods in this study may not be adequate to address it.

Three main methods used by the participants to remain productive and yet not cross the safety and workload boundary are given in table 6. By building on these already existing methods we can enhance the traditional safety training to improve their understanding and management of complex situations and errors; and mental risk assessment techniques. Such solutions when supplemented with the traditional training methods can improve safety, because simply increasing the emphasis on strict adherence to procedures and training based on those procedures is not adequate (Amalberti, 2001).

All participants when pressed for time and effort deviated from SOP after performing a on-the-spot mental risk assessment to determine if the deviation was safe. Five participants did not realize they were doing a mental risk assessment until it was pointed out at the interview. In this project, deviation from SOP was simply taken as moving closer to the safety boundary without assessing the nature of the deviation. It is true that all deviations would not have the same safety implications and based on the participants' opinion of SOPs (table 4), all participants felt that SOPs should be commensurate with risk and only 20% learned safety from the SOP as opposed to 100% from their mentors.

Are the SOPs too stringent and therefore what appears to be a deviation is not really unsafe at all and could even be beneficial? Amalberti *et al* (Amalberti, Vincent, Auroy, & de Saint Maurice, 2006) discus violations in healthcare saying that they can be useful in saving time and benefits both the system and individuals. However, it is essential to know which violations can and cannot be tolerated and they need to be monitored to ensure that they do not pose a risk. Such deviations may over time modify the behaviour of the workers to such an extent that the deviations will become normalised and lead to a major accident.

Deviations from SOP should be addressed firstly, by re-looking at the SOPs and revising them based on how laboratory work is done. This was correctly pointed out by one participant who said that people who make the SOPs (usually safety personnel) feel it is just one more step, why can't the laboratory worker just do it? In reality, that one step can delay the work throughout the day and hence the laboratory workers will deviate from it. Once the SOPs are written commensurate with risk taking into consideration how the laboratory works, workers can be taught to perform risk assessment for different situations and to exercise their degrees of freedom in a cautious and well-informed manner. Deviations from SOP can be looked at from yet another angle, the law of requisite variety proposed by Ashby in 1956 (Ashby, 1956). According to this law it takes variety to deal with variety, which means in order to solve a complex situation which is full of variety one needs to have solution which is also full of variety. This variety in the solution, which may be deviations from SOP, should not be taken as an error. However, these variations need to be carefully monitored and assessed in order to make sure they do not become dangerous.

Amalberti *et al* (Amalberti et al., 2006) has described the use of Rasmussen's model to study violations in aviation, train drivers, and rotary press and have explained three stages in the progress of a deviation to a dangerous level. Initially it is still a i) safe action; moving to ii) borderline tolerated condition of use (BTCU); and iii) normalization of deviance and reckless individuals. Managing deviations is not an easy task and requires in depth analysis and monitoring of the situation and will perhaps form the topic of another research.

Another practice that one participant talked about is sacrificing one goal in order to achieve another goal. If it was late at night and they were tired, they would still work but do the less risky tasks and leave the risky tasks for the morning when they were rested. This is a sacrifice judgement where the group collectively sacrifices one goal for another, in this case productivity vs safety. Such sacrifice judgements happen all the time and should be encouraged in a resilient organization (Woods, 2006).

This brings in another resilience building method that all the participants mentioned, that is open communication, trust and mentoring. Trust greatly influences safety because it encourages open sharing of information. One participant was very praising of her laboratory saying that they could approach the PI for anything including if their results were not good or there was an accident. It is through open sharing of information and mistakes that learning can be achieved as agreed by all the participants. In order to deploy the finite amount of resources towards productivity, it is necessary to gather and share all the information about hazards, situations faced by the workers how they responded and whether the outcome was positive or negative, these will all add to the rich learning process and can have a very positive influence on safety (McLain & Jarrell, 2007).

Mentorship and team work were methods to build resilience that all participants used. They were greatly dependant on the mentors for learning techniques and safety, if fact they did not seem to use other resources much. Mentors should be used as a conduit to reach to the individual laboratory members to teach them resilience building methods. Emphasis should be placed on small group discussions where people discuss how they dealt with situations and share their experience without any fear of reprisal. Woods (Woods, 2015) talked of four concepts of resilience, rebound, robust, graceful extensibility and sustained adaptability and these characteristics of a team can only be evaluated by observing how they work. This project only examined resilience in the form of anticipation and avoidance and not rebound after a disruption. One participant description of how they handled the unexpected delivery of a highly radioactive substance, which was new to them, by bringing together temporary shielding and team work, this is an example of graceful extensibility. These abilities are not learned in a formal training class; they are gained through experience and know-how and it is through open communications that this knowledge can be propagated.

CONCLUSION

This study focusses on applying Rasmussen's model of boundaries to a biomedical laboratory to understand the key goals faced by the workers and to plot the three boundaries for a biomedical laboratory. The results show that the most central goal was publications in top journals because the research team's very future depended on it. This was evident in the responses from the participants, therefore one of the three boundaries was the scientific output boundary, with the other two being workload and safety boundaries.

In addition, the project aimed at understanding the gradients that could push the OP towards the boundaries and the counter gradients that pushed the OP away from the boundaries towards the middle. Many factors were attributed to this, including the need to get good experimental results in order to be the first to publish, experiments being tedious and time sensitive, multiple simultaneous projects and resource scarcity. In order to deal with these factors and still remain productive, safe and avoid work overload due to excessive workload, workers mainly used three resilience building methods. Firstly, deviation from SOP based on a quick mental risk assessment in an attempt to save time and effort, secondly, team work so that they can plan the work such that each person gets a manageable amount of work. Team work also allowed them to watch out for each other to ensure that safety and productivity were not compromised. Lastly, gaining experience and familiarity through mentoring and on the job training such that they become very fluent in the techniques and processes. This also allows them the ability to do a better mental risk assessment as was seen in their responses that in the beginning of a new experiment they would take a lot more care and start omitting steps only as they got familiar with it.

Using the information obtained in this project, the next steps could be to improve the current training methods to add more training on risk assessment strategies, and to include scenario-based training using small group discussions or role play so that the resilience building methods they currently practice can be strengthened through tailored training. By pointing out to them the reasoning and structure in the intuitive methods they already use we can strengthen it.

Resilience cannot be achieved by adding more rules to deal with every situation, but by giving the right tools and knowledge to deal and monitor with the expected and unexpected situations that they face every day (Schafer, 2008). One possible approach to this could be a hybrid of rule-based and risk-based practices. Reason *et al* (Reason, Parker, & Lawton, 1998) talk of a customised portfolio perhaps a mixture of rule based non-negotiable instructions and the rest is based on their risk assessment. The rule-based organization-wide instructions will invite compliance when they are correct (commensurate on risk) and rewarding. These will always lack the requisite variety needed to deal with constantly changing work demands which need to be dealt with using local risk-based resilience building practices.

REFERENCES

Amalberti, R. (2001). The paradoxes of almost totally safe transportation systems. *Safety Science, 37* 109-126.

Amalberti, R., Vincent, C., Auroy, Y., & de Saint Maurice, G. (2006). Violations and migrations in health care: a framework for understanding and management. *Qual. Saf. Health Care, 15*, 66-71.

Amare, G. (2012). Reviewing the Values of a Standard Operating Procedure. *Ethiopian Journal of Health Sciences, 22*(3), 205-208.

Anderson, M. S., Ronning, E. A., De Vries, R., & Martinson, B. C. (2007). The Perverse Effects of Competition on Scientists' Work and Relationships. *Science and Engineering Ethics, 13*(4), 437-461. doi:10.1007/s11948-007-9042-5

Ashby, R. W. (1956). *An Introduction to Cybernetics*. London: Chapman & Hall Ltd.

Bernard, H. R., & Ryan, G. W. (2010). *Analyzing qualitative data: Systematic approaches*. Los Angeles California: SAGE.

Dejanović, D., & Heleta, M. (2016). An airport occupational health and safety management system from the OHSAS 18001 perspective. *International Journal of Occupational Safety and Ergonomics, 22*(3), 439-447. doi:10.1080/10803548.2016.1165387

Faunce, T. A. (2007). Nanotherapeutics: New challenges for safety and cost-effectiveness regulation in australia. . *Medical Journal of Australia,, 186*(4), 189-191.

Gill, P., Stewart, K., Treasure, E., & Chadwick, B. (2008). Methods of data collection in qualitative research: interviews and focus groups. *British Dental Journal, 204*(6), 291-295. doi:10.1038/bdj.2008.192

Gori, G. B. (2014). Elusive reproducibility. *Regul Toxicol Pharmacol, 69*(3), 279-280. doi:10.1016/j.yrtph.2014.05.020

Hale, A., & Heijer, T. (2006). Defining Resilience In E. Hollnagel, D. D. Woods, & N. Leveson (Eds.), *Resilience engineering : concepts and precepts*. England Ashgate Publishing Company.

Hangel, N., & Schmidt-Pfister, D. (2017). Why do you publish? On the tensions between generating scientific knowledge and publication pressure. *Aslib Journal of Information Management, 69*(5), 529-544. doi:doi:10.1108/AJIM-01-2017-0019

Hasle, P., & Zwetsloot, G. (2011). Editorial: Occupational Health and Safety Management Systems: Issues and challenges. *Safety Science, 49*(7), 961-963.

Hollnagel, E. A. (2013). Tale of two safeties. *Nuclear Safety and Simulation, 4*(1), 9.

Lay, E., Branlat, M., & Woods, Z. (2015). A practitioner's experiences operationalizing resilience rngineering. *Reliability Engineering and System Safety, 141*(63-73).

McLain, D., & Jarrell, K. (2007). The perceived compatibility of safety and production expectations in hazardous occupations. *Journal of Safety Research, 38*, 299-309.

McNutt, M. (2014). Reproducibility. *Science, 343*(6168), 229-229. doi:10.1126/science.1250475

Nemeth, C., Wears, R. L., Woods, D., Hollnagel, E., & Cook, R. (2008). Minding the Gaps: Creating Resilience in Health Care. Retrieved from http://www.ctlab.org/documents/Minding%20the%20Gaps-AHRQ%20AIPS%20Sep08.pdf

Rasmussen, J. (1997). Risk management in a dynamic society: a modelling problem. *Safety Science, 27*(2), 183.

Rasmussen, J., & Svedung, I. (2000). *Proactive Risk Management in a Dynamic Society:* . Retrieved from

Reason, J. T., Parker, D., & Lawton, R. (1998). Organizational controls and safety: The varieties of rule-related behaviour. *The British Psychological Society, 71*(4), 289-304.

Robson, L. S., Clarke, J. A., Cullen, K., Bielecky, A., Severin, C., Bigelow, P. L., . . . Mahood, Q. (2007). The effectiveness of occupational health and safety management system

interventions: A systematic review. *Safety Science, 45*(3), 329-353. doi:https://doi.org/10.1016/j.ssci.2006.07.003
Schafer, D., Abdelhamid, T. S., Mitropoulos, P., & Howell, G. A. (2008). I. (2008). *Resilience Engineering: A new paradigm for safety in lean construction systems.* Paper presented at the 16th Annual Conference of the International Group for Lean Construction.
Siegel, A. W., & Schraagen, J. M. C. (2014). *Developing resilience signals for the Dutch railway system.* Paper presented at the Proceedings of the 5th International Resilience Engineering Symposium: managing trade-offs, Soesterberg, The Netherlands.
Vaismoradi, M., Turumen, H., & Bondas, T. (2013). Content analysis and thematic analysis: Implications for conducting a qualitative descriptive study. *Nursing & Health Sciences, 15*(3), 398-405. doi:10.1111/nhs.12048
Van Noorden, R. (2011). A death in the lab. *Nature, 472*(7343), 270-271. doi:doi:http://dx.doi.org.libproxy1.nus.edu.sg/10.1038/472270a
Vijayan, V. (2017). *Taking the Risk to Think Differently about Hazard Management.* Paper presented at the 4th Asian Conference on Safety and Education in Laboratory, Singapore.
Vijayan, V., Mahalakshmi, R. N., & Lee, M. C. (2013). Integrating Safety in Science—How to Get Scientists' Buy-in. *Applied Biosafety, 18*(4), 172-177.
Walters, D., & James, P. (2011). What motivates employers to establish preventive management arrangements within supply chains? *Safety Science, 49*, 988-994.
Woods, D., & Hollnagel, E. (2006). Prologue: Resilience Engineering Concepts In E. Hollnagel, D. D. Woods, & N. Leveson (Eds.), *Resilience engineering: concepts and precepts.* England Ashgate Publishing Company.
Woods, D. D. (2006). Resilience Engineering: Redefining the Culture of Safety and Risk Management. *Human Factors and Ergonomics Society: Bulletin, 49*(12).
Woods, D. D. (2015). Four concepts for resilience and the implication sfor the future of resilience engineering. *Reliability Engineering and System Safety, 141*, 5-9.

APPENDIX

Appendix A: Participant informed consent form approved by the University Institutional Review Board

Participant Information Sheet and Consent Form

1. **Protocol title**
Exploring interdependencies between workload, production pressure and safety using Rasmussen's boundary model in biomedical laboratories

2. **Principal Investigator's with the contact number and organization:**

Viji VIJAYAN
Assistant Dean, Safety, Health and Emergency Management; and Procurement
Director, Research Operations
Duke-NUS Medical School 8, College Road Singapore 169857
Tel: (65) 6516 7249 Email: viji.vijayan@duke-nus.edu.sg

3. **What is the purpose of this research?**

There is a new concept in safety called resilience engineering (RE) which is used in industries like aviation and healthcare. This concept of RE propagates the concepts of performance variability and proactiveness as opposed to reactive control by standardizing performance in dealing with changing work place conditions. Biomedical laboratories are constantly facing new challenges and this study wants to understand that in the face of such challenges what are the goal conflicts that such organizations face. In particular, this study is interested in the conflict between production (eg paper publication), workload and your performance with regard to safety. Your participation will be in the form of interview(s) that I will conduct.

This study aims to:
- Explore the interdependencies between work load, output pressure and safety performance
- Understand the factors that affect safety performance
- Identify predictive indicators that one is moving close to the safety boundary and methods to move back into the safe zone

4. **Who can participate in the research? What is the expected duration of my participation? What is the duration of this research?**

Researchers working in a Duke-NUS laboratory (wet-bench), where the Principal investigator has agreed for his/her lab to take part in this study will be invited to take part in this study. A total of four laboratories will be invited to take part in this study and 3-4 persons working in each of the four laboratories will be invited to take part in this study.

- You will be interviewed once for 60-90 minutes, and a follow-up interview (30-45 minutes) will be arranged only if required to clarify some responses of the first interview; there will only be maximum of two interviews.

5. **What is the approximate number of research participants involved?**
Maximum 16 persons

6. **What will be done if I take part in this research study?**
You will be interviewed once and each interview will last approximately sixty to ninety minutes. If required to clarify some responses of the first interview, a second interview of about thirty to forty five minutes will be conducted. The interviews will be audio

Appendix B: Interview questions approved by the university Institutional Review Board:

1. Can you share what your lab/ organizational goals are?
2. Have you ever experienced production pressure in a project? How did that affect the planning of your experiments? How did they affect how you conducted the experiments? What were the important trade-offs?

3. Have you even been close to a safety incident or accident? Please describe the situation. Please describe how you noted that it was getting dangerous. How did you get there? How did you correct yourself?

4. Have you ever been close to a burnout or sick leave due to stress? Tell me about it. Is it related to particular project?