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A study of perceived workload and 'Levels of Automation' in Low-Dose Rate Brachytherapy

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Table of Contents

List of Figures

List of Tables

Executive Summary

A study of perceived workload and 'Levels of Automation' (LOA) was performed at the 'Treatment delivery' stage of Low-Dose Rate (LDR) prostate brachytherapy, which is a modality of cancer treatment. Five research questions were researched on the topics of perceived workload, automation, 'levels of automation', and automation-related issues, such as trust in automation, reliance on automation, perceived reliability of equipment performance, and 'preferred LOA' in LDR prostate brachytherapy. LDR prostate brachytherapy was mapped among the core team members by using a Hierarchical Task Analysis: Radiation oncologists, Radiologists (where applicable), Medical physicists, Nurses, and Anaesthetists. NASA-TLX was applied to the core team members' main operations in order to assess the perceived workload straight after each of the 48 LDR prostate brachytherapy treatment cases carried out across four hospital sites in Ireland, and also to identify the critical perceived workload levels that could compromise patient safety among the core team members. Low, but still an acceptable workload was identified among Radiation oncologists. High, but still an acceptable workload was identified among Medical physicists, Nurses and Anaesthetists. No critical workload levels were identified. The main three predominant TLX dimensions were "Mental Demand", "Temporal Demand" and "Effort". A 'Modified Levels of Automation' (MLOA) model for brachytherapy with four LOA action stages previously identified by Parasuraman et al. (2000) "Information Acquisition", "Information Analysis", "Decision Selection", and "Action Implementation", was developed and applied to the current LDR prostate brachytherapy system. A 'MLOA' identified medium LOA at "Information Acquisition" action stage among the Radiation oncologists and Anaesthetists, and low LOA among the rest of the core team members at the other three LOA action stages. Small and moderate correlation between the perceived workload and 'MLOA' action stages was found among the Radiation oncologists & Radiologists, and between Medical Physics team in the present system, and a strong correlation for the Medical physicist #2 in the future system. ANOVA has shown that there are differences between the levels of perceived workload and 'MLOA'. In future systems the higher LOA will result in reduced core team members' operations. Their roles will change into supervisory roles; the perceived workload will stay at optimal levels, while the level of patient safety remains exceptional.

Declaration

I hereby declare that my submission is the result of my own work and as a whole is not substantially the same as any that I have previously made or am currently making, whether in published or unpublished form, for a degree, diploma, or similar at any university or similar institution.

______________________ Date: ___________

Matjaz Galicic

Published Work

The following is a list of relevant publications presented and published based on the work presented in this thesis:

Conference papers

Galičič, M., Fallon, E., van der Putten, W. Sands, G., 2015, An Investigation of the Relationship Between Perceived Workload and 'Levels of Automation' of Radiation Oncologist at 'Treatment Delivery'Stage of Low-Dose-Rate Brachytherapy, Proceedings of the Irish Ergonomics Society Annual Conference 2015, " Human Factors and Ergonomics for Safety Critical Domains: Contributions From Professional Experiences ", Trinity College Dublin, 18 June 2015, Irish Ergonomics Society, ISSN 1649-2102

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Abstract and poster presentations

Galičič M., Fallon E., van der Putten W., Sands G. (2014), Hierarchical Task Analysis of Medical Physicist's task at seed implantation stage of Low-Dose Rate prostate brachytherapy cancer treatment, Proceedings to the NUI Galway – University of Limerick Alliance First Annual Engineering and Informatics Research day, University of Limerick, 25 May 2014 (poster and abstract)

Galičič M., Fallon E., van der Putten W., Sands G. (2013), Applying NASA-TLX to Prostate Seeds Brachytherapy, IEHF Patient & Healthcare Provider Safety conference, London, 25 November 2013; www.ergonomics-protects.org.uk (poster only).

Galičič M., Fallon E., van der Putten W., Sands G., 2013, Measuring Physicians' Workload at Seed Implantation Stage of Prostate Brachytherapy Treatment Using NASA-TLX Method, NUI Galway - UL Alliance Engineering, Informatics and Science Research Day 2013 - Book of Abstracts, Madden, M.,Ó Brádaigh, C. (eds.), NUI Galway, 11 April 2013, available at http://aran.library.nuigalway.ie/xmlui/handle/10379/3345 (poster and abstract)

Galičič M., Fallon E., van der Putten W., Sands G., 2012, System Interaction in MammoSite High-Dose Rate Brachytherapy using Systems Safety and User-Centered Design Principles, iHCI 2012: Proceedings of the Sixth Annual Irish Human Computer Interaction (HCI) Conference - Poetics of Design, Narratives of Use, NUI Galway, 20-21 June 2012, ISBN 978-1-908358-07-3 (poster only)

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List of Abbreviations

2D	Two Dimensional
3D	Three Dimensional
4D	Four Dimensional
AAPM	American Association of Physicists in Medicine
ABS	Anti-lock Breaking System
ACS	American Cancer Society
ADR	European Agreement concerning the International Carriage of Dangerous Goods by Road
AI	Artificial Intelligence
ASTRO	American Society for Radiation Oncology
CAED	Cause and Effect Diagram
CAT	Computerised Axial Tomography
CEV	Crew Exploration Vehicle
CIS	Carcinoma In Situ
Co-60	Cobalt 60
COHSEE	Centre for Occupational Health & Safety Engineering and Ergonomics
CT	Computerised Tomography
ECRP	Error-Cause Removal Program
EF	Effort (a TLX dimension)
EPID	Electronic Portal Imaging Device
EPR	Electronic Patient Record
EU	European Union
FDA	Food and Drug Administration
FLOAAT	Function-Specific LOA and Automation Tool
FMEA	Failure Modes and Effect Analysis
fNIR	Functional Near Infra-Red
FR	Frustration (a TLX dimension)
FTA	Fault Tree Analysis
G-M	Geiger-Müller
GPS	Global Positioning System
GY	Gray

HACCP	Health Analysis and Critical Control Point
HACT	Human-Automation Collaboration Taxonomy
HAZOP	Hazard Operability Study
HDR	High-Dose Rate (Brachytherapy)
HFMEATM	Health Failure Mode and Error Analysis TM
HMI	Human Machine Interaction
HTA	Hierarchical Task Analysis
HRB	Health Research Board of Ireland
HSE	Health Service Executive (UK)
IDEF	Integration Definition for Function Modelling
IAI	Intelligent Adaptive Interface
ICS	Irish Cancer Society
IDEFØ	Integrated Computer Aided Manufacturing DEFinition for Function Modelling
IEA	International Ergonomics Association
I-125	Iodine-125
Ir-192	Iridium-192
ISO	International Organisation for Standardisation
LDR	Low-Dose Rate (Brachytherapy)
LOA	Level(s) of Automation
LOC	Level of Competence
LOI	Level of Information
LDR	Low-Dose Rate (Brachytherapy)
LSD	Least Significant Difference
mCi	Millicurie
MD	Mental Demand (a TLX dimension)
MDR	Medical Device Report
MMSA	Man-Machine Systems Analysis
MRI	Magnetic Resonance Imaging
NASA	National Aeronautics and Space Administration
NCRI	National Cancer Registry Ireland
NUIG	National University of Ireland, Galway
OPW	Overall Perceived Workload
ORP	The Office of Radiological Protection

OTAS	Observational Teamwork Assessment for Surgery
PACT	Pilot Authorisation of Control of Tasks
PD	Physical Demand (a TLX dimension)
PE	Performance (a TLX dimension)
PSA	Prostate Specific Antigen
QA	Quality Assurance
RCA	Risk Cause Analysis
ROSSA	Radiation Oncology Systems Safety Analysis
SA	Situation Awareness
SHC	Stanford Health-Care
SHN	Sutter Health Network
SHERPA	Systematic Human Error Reduction and Prediction Approach
S.I.	Statutory Instruments
SOP	Standard Operating Procedure
SWAT	Subjective Workload Assessment Technique
SWORD	Subjective Workload Dominance
TA	Task Allocation
TD	Temporal Demand (a TLX dimension)
TLX	Task-Load Index
TNM	Tumour-Node-Metastasis
TRUS	Trans-Rectal Ultra-Sound (probe)
TWA	Team Workload Assessment
UCD	User-Centred Design
WHO	World Health Organisation

Chapter 1: Introduction

1.1 Chapter overview

This chapter introduces the background to this thesis. It provides a short description of the background to this research project, it lists the relevant key words, it provides some theoretical background to the topics of healthcare technology, radiotherapy safety, human factors, healthcare human factors, and workload. The aims and objectives of this research are provided, as well as research questions and thesis structure.

1.2 The ROSSA project

The Radiation Oncology Systems Safety Analysis (ROSSA) project was approved by the Health Research Board (HRB) of Ireland. It involved researchers from National University of Ireland, Galway (NUIG)'s Centre for Occupational Health & Safety Engineering and Ergonomics (COHSEE), College of Engineering and Informatics, and NUIG School of Physics. Work included cooperation with the Radiotherapy Departments in Galway University Hospitals and other private and public hospitals in Ireland.

The main objective of the ROSSA project was to develop a set of workable tools for use within a Radiotherapy Department, which will allow the users of the department to analyse risks and hazards in a systematic manner, taking into account the actual patient and data flow.

A second objective was to provide a comprehensive risk analysis of existing and future advanced Radiotherapy technologies, and to support the development of strategies for error reduction in such systems, with the emphasis on the interaction between the technology and treatment staff.

The overall benefit of the ROSSA project would be a Risk assessment system that is based on standards formed in Healthcare and its related industries, such as Nuclear, Aviation, etc.

1.3 Key words

The following are keywords relevant to the ROSSA project (in alphabetical order):

Automation, Brachytherapy, Ergonomics, Human Factors, Human Factors Engineering, Human Performance, 'Levels of Automation', Radiotherapy, Safety, Workload.

1.4 The evolution of healthcare technology and radiotherapy safety

The industrial revolution started in the late 18th century when the first steam machines were created, and continued throughout the 19th century, when the first examples of modern manufacturing plants were built for mass production. Since then, most of the technological progress we know today happened in the last 115 years, especially before, during, and after World War I and World War II. These two events created a rapid development in the aviation industry, nuclear industry, military industry, and automotive industry, among others. After World War II, the technologies of industrial systems and hospitals merged, especially the technology that was developed and used for utilising treatment of patients diagnosed with cancer. The successful design and use of the technology contributes to safer and more effective treatment of cancer patients. Three modern examples of advances in medical technology are:

- X-Ray machines merging with computer processors creating Computerised Tomography (CT) machine, also known as X-ray CT or CAT (Computerised Axial Tomography) scan
- The replacement of the Cobalt-60 machine with linear accelerator
- The development and use of Trans-Rectal Ultrasound (TRUS) in prostate seed brachytherapy.

The German scientist Wilhelm Roentgen developed X-ray machine in 1895. X-ray machines helped with doctor's diagnosis and improved treatment of patients. X-ray machines have evolved from conventional X-ray machines where the "X-ray beam merges through a thin glass window in the tube envelope" (Khan 2003). Besides the dangerous electromagnetic radiation in a wavelength as emissions, it could only produce a 2-dimensional image on a film. X-ray machines evolved into a CT scan, which incorporates X-ray technology and produces a 3-dimensional image, presented on a computer display.

The Cobalt-60 (Co-60) radiation therapy machines which were invented in 1951 by Canadian Dr. Harold Johns (London Health Sciences Centre 2011; University of Saskatchewan n.d.) were actually storing Co-60, a highly radioactive source, are now outdated. They have been replaced with machines which use different technology for cancer treatment, called linear accelerators, or "Linac's" for short. While the treatment objective is to treat the patient by exposing him or her to the radiation source, the concept of delivering the radiation has changed. The radioactive source is no longer contained in the machine. The radioactive beam is now created by accelerated photons, elementary particles of radiation, which are created within the machine as high energy X-ray beams (hence the name "linear accelerator"), and can be delivered very accurately, up to half a millimetre. Newer linear accelerators produce electrons, and are designed to cover areas on, or close to the skin. In both cases, the beam is shaped, and delivered though the collimators, which help to shape the beam with a high precision into the patient's body, destroying cancerous cells, and sparing healthy cells and vital organs.

Trans-Rectal Ultra-Sound (TRUS) prostate biopsy using transperineal approach has been introduced in the early 1930's (Porter and Wolff 2014). At present TRUS is extensively used for prostate biopsy and for prostate seed brachytherapy treatment. TRUS was successfully applied for the implantation of the I-125 radioactive seeds in the mid-1980's by Holm et al. (1983). It transformed the "free-hand" radioactive seed implantation technique which was in use before that (Porter, Blasko et al. 1995). The technology made the treatment process faster, more precise, efficient, and overall, safer to the patient. Nowadays software compliments the TRUS output, it creates a 2- or 3-dimensional model of the implanted seeds and calculates the overall dose of these implanted seeds, called the "isodose". More details about radiotherapy and brachytherapy are in the next chapter.

Nowadays human operators can do very little work without the support of technology. Technology that supports the human operators is everywhere, sometimes even without us humans realising it. Examples of automation are:

- Transport: automatic gear system, Anti-lock Breaking System (ABS), Global Positioning System (GPS), etc.
- Time management: alarm clocks, software applications, etc.
- Communication: Short Message Service (SMS), saved numbers in a mobile phone, the ability to see the person we talk to on the screen, etc.
- Television: stored TV stations, TV screen settings, TV programme recording options, etc.)
- Travelling: train/bus waiting time displays, etc.
- Data storage: servers with easy and direct access, remote access to data, etc.
- High-end linear accelerators: they are able to deliver treatment to patients with cancer.

1.4.1 Technology

Technology is designed and interconnected to help and to support human tasks, and/or to perform tasks that humans are unable to do. The technology can already exceed human capabilities, e.g. robots in the car manufacturing industry assembling cars, or linear accelerators delivering radioactive treatment dose to the patient. Because the technology is rapidly evolving, the “old” and “outdated” equipment in radiotherapy is replaced with new equipment every five to ten years, or whenever the financial situation of the hospital department allows it. New computers, updated network systems, new high-end machines, etc., can be outdated in three to five years. Introducing such new technology, especially high-end machines, such as linear accelerators is very expensive. People working in the healthcare environment have to cope with the new technology introduced to them. They have to ensure the technology is set-up and commissioned safely, that it is working safely, that it is used safely, they have to maintain it, have it serviced, perform quality assurance checks, etc.

Technology therefore compliments human performance, and it makes the performance more efficient for the healthcare staff, and also, it makes the cancer treatment more efficient for the patient. If the technology in use is not complimenting a workers' performance, the healthcare staff may experience interaction problems with technology. Interaction problems influence workload. In case of inadequately met workload, be it low or high, negative work indicators may appear. These are fatigue, boredom, frustration, decreased attention, lost motivation, physical and mental stress, time pressure, inability to cope with the given situation, problems with making decisions, etc. The study of human performance, workload and the study of technology, or 'automation' are part of the "systems safety approach", where such contributing factors are looked at closely. This science is known as "Human Factors Engineering"; it is also often referred to as "Ergonomics".

1.5 Human Factors

The International Ergonomics Association (IEA) defines *Human Factors* (or Ergonomics) as (IEA n.d.):

"Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance."

Health and Safety Executive (HSE) (UK) defines *Human Factors* as (HSE n.d.):

"Human factors refer to environmental, organisational and job factors, and human and individual characteristics, which influence behaviour at work in a way which can affect health and safety"

Three aspects of job design should be included: the job (e.g. the nature of the task, workload, the working environment, etc.), the individual (e.g. personal competence, skills, attitude, risk perception, etc.) and the organisation (e.g. work patterns, safety culture, communication, etc.) (HSE n.d.).

Chapter 1: Introduction

World Health Organisation (WHO) defines Human Factors as (WHO 2011):

"Human factors is an established science that uses many disciplines (such as anatomy, physiology, physics and biomechanics) to understand how people perform under different circumstances. We define human factors as: the study of all the factors that make it easier to do the work in the right way."

The terms "Ergonomics" and "Human Factors" refer to the same science. The word "Ergonomics" derives from two Greek words, "ergon" and "nomos", which means "work" and "law", and may be described as the "science of work" (Parker 2015). The discipline is often referred to as "Human Factors Engineering", which essentially researches the interaction between the human, the machines (or "the technology"), and their interaction (Meister 1999). It takes into account the physical and cognitive characteristics of the interaction, which can be an interaction between people, or with machines, e.g. with a single person or a machine, a number of people or machines, or sets of complex man-machine systems. It uses a number of scientific methods to support, improve system performance and to create a safe working environment that prevents accidental harm (Scanlon and Karsh 2010; Parker 2015). World Health Organisation (WHO) provides a good description of Human Factors Engineering (WHO 2011):

"Human Factors Engineering seeks to identify and promote the best fit between people and the world within which they live and work, especially in relation to the technology and physical design features in their work environment."

Similar to the rapid development of technologies, Human Factors expanded before, during and after World War I and II. It contributed to the design of machines, technologies, working environment, job satisfaction, and safety. It incorporated the human perspective to safety, design, training, new product development, e.g. to the design of car, train and airplane cabins, design of controls, consumer products, machine functions, etc. It was applied in numerous disciplines, e.g. transportation, computer hardware and software, aerospace, military, medical device, healthcare, oil & gas, manufacturing, mining, forestry, nuclear industry, safety & accident investigations, etc. The four main Human Factors disciplines are: physical ergonomics, cognitive ergonomics, social or organisational ergonomics, and neuro-ergonomics. Because it is an interdisciplinary discipline, it often involves people from different disciplines working together, e.g. Psychologists, Physiotherapists, Designers, Mechanical engineers, Software engineers, Health & Safety practitioners, as well as people from other domains, e.g. Medical Doctors, Nurses, Anaesthetists, Therapists, etc., working in the healthcare environment.

1.6 Healthcare Human Factors

The focus of “Healthcare Human Factors” is on the healthcare environment. It includes systems safety design, patient safety, medical devices, medical device usability and design, and User-Centred Design (UCD) principles, etc. (Galičič, Fallon et al. 2013; Galičič, Fallon et al. 2013). The focus on Human Factors in Healthcare has increased since the “To Err is Human: Building a Safer Health System” report (Kohn, Corrigan et al. 2000). This report emphasised the need to approach healthcare systematically and with the focus on patient safety, in particular when identifying and reducing errors. It increased collaborations among health science researchers and other disciplines for new approaches towards patient safety, including Human Factors Engineering (Stelfox, Palmisani et al. 2006). World Healthcare Organisation outlined the importance of human factors in healthcare as an important issue in terms of recognising the potential for error, developing strategies and systems to learn from mistakes so as to minimise their occurrence and effects (WHO 2011).The emphasis on human performance and training moved on to the understanding of cognitive work in terms of systems safety (Parker 2015). Human Factors Engineers are encouraged to work along with the healthcare practitioners to help improve the healthcare working environment and to observe the effects that the improvements have on patient safety (Gurses, Ozok et al. 2011; Parker 2015).

The term “Healthcare Human Factors” is often applied to clinical settings, and is therefore also referred to as “Clinical Human Factors”. The Clinical Human Factors Group (CHFG n.d.) quotes Dr. Ken Catchpole, a Human Factors expert when providing the definition of “Clinical Human Factors”:

“Enhancing clinical performance through an understanding of the effects of teamwork, tasks, equipment, workspace, culture, organisation on human behaviour

and abilities, and application of that knowledge in clinical settings."

The Healthcare Human Factors discipline has grown into numerous specialist groups and centres at national and international level, e.g. the Irish Centre for Patient Safety (Ireland), The National Centre for Human Factors in Healthcare (USA), Healthcare Human Factors (Canada), The Clinical Human Factors Group (UK), National Patient Safety Agency (UK), and the Patient Safety Translational Research Centres (UK), etc.

1.7 Healthcare Human Factors and workload

Healthcare Human Factors focus has expanded from focusing on errors to other human factors aspects as well, especially in relation to human-human interactions and human-automation interactions. Examples include research in scheduling, teamwork, communication patterns, shift work, fatigue, stress and workload. Workload is especially important because when it is too high or too low, it can often lead to fatigue, boredom, frustration, decreased attention, physical and mental stress, inability to cope with the given situation, and to increased intentional or unintentional errors which can potentially compromise patient safety. Workload as a human perception construct, critical levels of workload and its relation to technology (also referred to as 'automation') are the core topics of this thesis, and will be researched and explained in more details in later chapters of this thesis.

1.8 Research questions

The objectives of this research project which is built on ROSSA project objectives were to support the development of strategies for the reduction of errors in radiation therapy systems, with particular emphasis placed on the interaction between the technology and treatment staff. The objectives match "To Err is Human: Building a Safer Health System" report (Kohn, Corrigan et al. 2000) which highlighted the importance of applying Human Factors principles to radiotherapy in order to improve patient safety. The research questions are one of the approaches towards addressing the issue of radiotherapy safety, and in particular, the issues with perceived workload and human-automation interaction in Low-Dose Rate (LDR) prostate brachytherapy treatment.

This thesis resolves the following five research questions:

1. What are the critical levels of perceived workload among working professionals at the "Treatment delivery" stage of Low-Dose Rate prostate seeds brachytherapy treatment that could compromise patient safety? This question was answered in Chapter 4.
2. Which core team members' operations do the critical perceived workload levels appear with? This question was answered in Chapter 4.
3. How can 'Modified Levels of Automation' be applied to Low-Dose Rate prostate brachytherapy? This question was answered in Chapter 5.
4. How does perceived workload relate to the 'Modified Levels of Automation' in the present Low-Dose Rate prostate brachytherapy system? This question was answered in Chapter 7.
5. How will the perceived workload relate to the 'Modified Levels of Automation' in the future Low-Dose Rate prostate brachytherapy system? This question was answered in Chapters 8 (which includes the indications/information to this answer in Chapters 6 and 7).

1.9 Methodology synopsis

The following steps were carried out to address the research questions:

1. Process mapping and familiarising with the LDR prostate brachytherapy process: thirty two LDR brachytherapy treatment cases were observed prior to data collection to map operations and sub-operations performed by brachytherapy team during the "Treatment delivery" stage. Informal interviews, questions and answers and written notes were used for mapping. Hierarchical Task Analysis was used to model the work process for each team member at the "Treatment delivery" stage of LDR prostate brachytherapy.

2. Assessment and analysis of perceived workload using NASA-TLX method:

A simple and easily applicable technique was applied to study perceived workload in the present clinical LDR prostate brachytherapy environment. For the purpose of this research, a paper-based NASA-TLX technique was applied to each core team member separately. Each team member had to fill out a TLX worksheet prepared specifically for their role and matched previously developed operations. The TLX worksheets were applied straight after the LDR prostate brachytherapy treatment was finished. Analysis followed the standard NASA-TLX guidelines, where the overall workload score was calculated, as well as the proportion of each TLX dimension. Furthermore, minimum and maximum values, as well as mean, median and standard deviation were calculated and presented for each team member's operation individually. The 'Revised workload rating scale' was applied to the overall workload scores, categorising the scores as low, moderate or high workload. The 'Revised workload rating scale' also helped to identify the 'red-line levels', for when the workload was "too low" or "too high". The red-line levels could potentially compromise patient safety, and were classified as "acceptable" or "unacceptable". Applying the 'Revised workload rating score' and identifying the 'red-line levels' researched the first two research questions: (1) What are the critical perceived workload levels, and (2) which core team members' operations do the critical perceived workload levels appear with.

3. The development of a 'Modified Levels of Automation' model in LDR prostate brachytherapy: Out of the several "Levels of automation" models presented in the literature review, two most suitable LOA models were shortlisted and modified into a single LOA model to fit LDR prostate brachytherapy. This step researched the third research question on the applicability of LOA models to LDR prostate brachytherapy.

4. The "Human-Automation" questionnaire: The purpose of the questionnaire was to examine how users interact in the present automated system. It also assessed how users interact with automation; it examined trust in automation and provided additional data to address the 'preferred LOA', that is, which LOA would users prefer to have in the future automated systems. This step

provided the indicators for the investigation of the relationship between perceived workload and “Levels of automation” in the future LDR prostate brachytherapy system.

5. The investigation of the relationship of perceived workload and ‘Modified levels of automation’ in LDR prostate brachytherapy: Pearson’s Correlation coefficient was used to investigate the relationship between the perceived workload and “Levels of automation” in the present LDR prostate brachytherapy system. This step researched the fourth research question. “How does perceived workload relate to the ‘Modified Levels of Automation’ in the present Low-Dose Rate prostate brachytherapy system?”, and provided indications on the fifth research question: “How will the perceived workload relate to the ‘Modified Levels of Automation’ in the future Low-Dose Rate prostate brachytherapy system?”

1.10 Thesis structure

The remainder of the thesis is presented in eight chapters:

- Chapter 2 – General literature review on the topics of radiotherapy, brachytherapy, and Low-Dose Rate brachytherapy
- Chapter 3 – Mapping Low-Dose Rate brachytherapy treatment
- Chapter 4 – Workload
- Chapter 5 – Automation and ‘Levels of Automation’
- Chapter 6 – Human-Automation related issues
- Chapter 7 – The investigation of the relationship between perceived workload and ‘Modified Levels of Automation’ in Low-Dose Rate prostate brachytherapy
- Chapter 8 – General discussion and application of workload and ‘Levels of automation’ to future automation systems
- Chapter 9 – Research summary and conclusions

1.11 Chapter summary

This chapter introduced the topic of healthcare technology, radiotherapy safety, human factors, healthcare human factors and workload. The aims and objectives of this research were provided, as well as the thesis structure on a chapter-to-chapter basis. The next chapter will introduce the topics of radiotherapy, brachytherapy, workload, automation, and ‘Levels of Automation’ in more details.

Chapter 2: General Literature Review: Radiotherapy, Brachytherapy and Low-Dose Rate Brachytherapy

2.1 Chapter overview

This chapter introduces the topics of cancer, radiotherapy, brachytherapy and Low-Dose Rate brachytherapy, radiotherapy safety issues, and Irish and EU legislation related to radiotherapy.

2.2 Cancer, Radiotherapy, Brachytherapy and Radiotherapy safety issues

2.2.1 Cancer

According to the World Health Organisation (WHO), cancer contributed to 13% of all deaths worldwide in 2008 (WHO 2015). The majority of cancer deaths were caused by prostate cancer, stomach cancer, breast cancer, and colorectal cancer. High income countries, including Ireland, had more than double the rate of all cancers combined of low income countries in 2008 (WHO 2015). In Ireland, one out of three people will develop cancer during their lifetime (ICS 2015).

Cancer can be described as “an abnormal growth of cells” (SHC 2015). Cancerous cells keep growing and reproducing and look differently to healthy cells. They can form tumours, which is an abnormal growth of tissue. The term “tumour” is used when the cells can cause harm, or even death. “Malignant” tumour is cancerous, and their cells grow and spread fast. Malignant tumour is also referred to as the “primary” tumour. If a cell or group of cells enter the bloodstream or lymphatic system, they can create a “secondary” tumour, or “Metastasis”. The cells of “benign” tumour tend to grow slowly and do not spread to the other parts of the body, so it is not called cancer (ICS 2015; SHC 2015).

2.2.2 Prostate cancer

Prostate cancer is the most common cancer after skin cancer and lung cancer in the United States (ACS 2014). It is one of the five most common cancers in Ireland, together with non-melanoma skin cancer, breast cancer, bowel cancer and lung cancer (ICS 2015). The estimates for 2015 for the United States are about 220,800 new cases of prostate cancer and about 27,450 deaths from prostate cancer (ACS 2014). It is mostly diagnosed in men aged 65 or above. About 1 in 38 men will die of prostate cancer in the United States (ACS 2014). However, not all men will die from it after they are diagnosed. In Ireland, there are 3,267 new cases of prostate cancer every year. The median age for men diagnosed with prostate cancer is 67, and the median age for death from prostate cancer is 80 (NCRI 2013).

According to the American Cancer Society (ACS), after including all stages of prostate cancer, the relative 5-year survival rates of men that were diagnosed with prostate cancer is almost 100%, the relative 10-year survival rate is 99%, and 15-year relative survival rate is 94% (ACS 2014). Men in the United States had the highest rates of prostate cancer, followed by Europe (WHO 2015). Ireland, for instance, has approximately 93% 5-year relative survival rate for prostate cancer (NCRI 2013). The word “relative” in the above cases is used because some men will die of other causes than prostate cancer (ACS 2014).

2.2.3 Radiotherapy

Oncology is the discipline of studying and treating cancers and tumours. Radiation therapy is a common form of cancer treatment in Ireland and elsewhere in the world. It is often referred to as “Radiotherapy”. It uses high-energy X-rays to destroy cancerous cells and to shrink tumours.

Radiotherapy is a “curative” (or “radical”) treatment because it is prescribed by doctors to cure symptoms, pain, etc., that is, to destroy cancerous cells and as a consequence, improves patient’s quality of life and prevents the risks recurring. On the other hand "palliative" treatment masks, relieves or delays symptoms of the disease and is often used at later stages of cancer, and may be combined with surgery, chemotherapy, etc.

There are two different types of radiotherapy:

1. External-Beam Radio-Therapy (EBRT), which is also referred to as the radiotherapy that works "from the inside, out" (BrachyAcademy n.d.)
2. Internal Radiation Therapy, also known as brachytherapy, is also referred to as the radiotherapy that works "from the outside, in" (BrachyAcademy n.d.).

2.2.4 External-Beam Radiotherapy

External Beam Radiotherapy (EBRT) uses Linac machine as a principle technology for cancer treatment, and as described previously, it produces a highly radioactive beam that is produced and aimed at cancerous cells at high precision. Because of this technology, the patient is not exposed to any radioactivity. The treatment is very specific and only affects the area being treated. It is designed to spare the healthy cells and organs, although some side effects can appear with the patient, e.g. fatigue, tiredness, red and/or itchy skin, etc. (NIH 2010). The patient typically receives one treatment (which is also referred to as a "fraction") daily, five days a week, totalling to 10-20 fractions over 2-10 weeks. The number of fractions corresponds to the dose per fraction, which sums up to the total dose of radiation prescribed and received per treatment case. The total dose of radiation varies from patient to patient and depends on the tumour size, tumour location, stage of cancer, general health of the patient, other treatments the patient is receiving, etc. The dose units are expressed in International System of units called "Gray" (Gy). Gy is the unit of absorbed dose of ionising radiation deposited per unit of tissue. 1 gray = 1 Joule/kilogram and also equals 100 rad. "Rad" is the unit of absorbed dose of ionizing radiation as an equal amount of radiation that releases an energy of 100 ergs per gram of matter or 0.01 joule per kilogram of irradiated material. "Erg" is a unit of energy and mechanical work equal to 10^{-7} joules and is not an International System unit. 1 rad = 0.01 Gy = 0.01 Joule/kilogram. Rad is nowadays only used in the United States; Gy is used elsewhere since it has been introduced as a standard unit by the International System of Units in 1975.

The following list shows a few different modalities of EBRT which include different imaging and machine-treatment principles (the list is not exclusive):

a) Intensity-Modulated Radiation-Therapy (IMRT): the dose is matched to the shape of the rays to match the tumour
b) Stereotactic radiotherapy: it uses images to pinpoint the location of small tumours
c) 3D Conformal radiotherapy (also known as “3-Dimensional” or “3D” radiotherapy): it combines images from IMRT and CT scan to create a 3D model of the tumour
d) Image-Guided Radiation-Therapy (IGRT): daily CT scans are used to create a 3D image of the tumour

Radiotherapy as a treatment is not an exclusive modality of cancer treatment. Sometimes it is combined with adjuvant therapy, which is an additional cancer treatment given after the primary treatment to keep cancer from returning. Besides radiotherapy, it may also include chemotherapy, hormone therapy, etc.

2.2.5 External-Beam Radiotherapy stages, staff roles and responsibilities

The EBRT process consists of many specific stages, operations and sub-operations, which require specialised knowledge and equipment. Based on the process map by Ford *et al.* (2012), EBRT stages are presented in Figure 2-1. They are described in more details in Table 2-1 (WHO 2008).

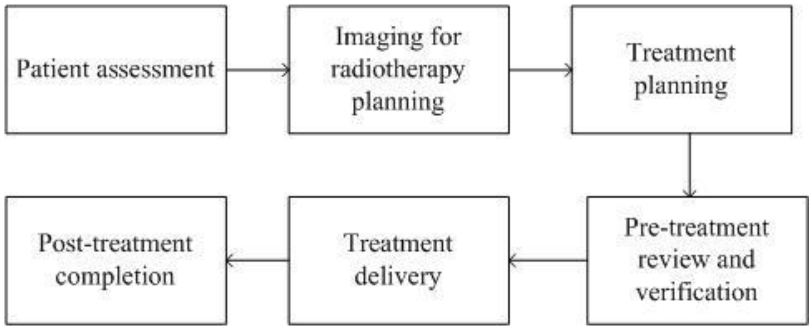


Figure 2-1 External Beam Radio-Therapy stages

Staff working in Radiotherapy is part of an interdisciplinary team. Staff members are highly skilled and competent to perform their role. Examples of staff roles and responsibilities involved in radiotherapy treatment are described in

Table 2-2 (AAPM 1993; WHO 2008; Ford, Fong de Los Santos et al. 2012; SHN 2013; ICS 2015).

The American Association of Physicists in Medicine (AAPM) Report #45 provides guidelines for the Code of Practice for radiotherapy accelerators, including facility planning and radiation protection, acceptance testing, treatment planning, dosimetry, Quality Assurance (QA) guidelines, maintenance and operation of the machine, etc. It also provides a definition of a qualified Medical physicist and instrumentation needed for acceptance testing and commissioning of radiotherapy accelerator (Nath, Biggs et al. 1994).

Table 2-1 External Beam Radio-Therapy stages in details

Stage	**Description**
Patient assessment	• Patient is assessed and diagnosed by the Radiation oncologist based on their symptoms, physical examination, lab results, tumour stage, tumour extent, etc. • Consideration of guidelines and patient wishes • Diagnosis and protocol decision
Imaging for radiotherapy planning	• Patient is positioned correctly; reference points and guides are marked

Stage	**Description**
	• CT, MRI, X-ray and/or ultrasound imaging is performed to determine the exact location of the patient's tumour, tumour size to be treated • Contouring is performed; margins are applied around tumour volume • Images are exported to the cancer treatment database
Treatment planning	• Contouring: after the images are reviewed, the cancerous cells are highlighted and healthy cells are shielded • Total dose, dose per fraction, number of fractions, beam energy, beam size, etc. are prescribed using planning software
Pre-treatment review and recommendation	• The plan is reviewed by Radiation oncologist and other radiotherapy staff, e.g. Medical physicists, Dosimetrists, etc. • Optimal plan for cancer treatment is recommended and approved • Treatment plan is exported to the treatment machine
Treatment delivery	• The patient is placed in treatment position for each treatment and monitored throughout the treatment • The planned dose is physically delivered in a number of fractions on a designated radiotherapy machine
On-treatment quality management	• Monitor of the daily setup • Deliver radiotherapy treatment in accordance with departmental protocols • Monitor tolerance by regular patient review
Post-treatment completion	• Confirmation of treatment delivery • Patient has a consultation with the Radiation oncologist about their treatment • Patient follow-up as agreed with Radiation oncologist
Equipment and software quality management	• Daily, weekly and monthly QA of the treatment plan and cancer treatment devices is performed

Table 2-2 Example of staff roles and responsibilities in radiotherapy

Staff	**Roles and responsibilities**
Radiation oncologist	i. A consultant medical doctor who specialises in treating cancer patients using radiotherapy ii. Sees referred patients who are scheduled to receive radiotherapy for cancer treatment iii. Determines the exact field or area to be treated by radiation and prescribe the number of treatments needed iv. Plans review and approval of cancer treatment v. Monitors the treatment vi. Follows up the patient
Radiation therapist	i. Specialises in planning and delivering radiation to patients with cancer and other conditions ii. Works with the patient, e.g. provides patient information and support, schedules the patient, etc. iii. Monitors the patient's progress during their treatment iv. Produces and checks treatment plan v. Performs simulation and planning vi. Positions the patient vii. Operates the equipment to deliver the radiation viii. Verifies treatment ix. Monitors the patient on a daily basis
Medical Physicist	i. A radiation expert who helps to plan the treatment with the radiation therapy team ii. Plans for resource allocation with Radiation oncologists, administrators and technologists, e.g. equipment usage, selection and replacement of equipment, budget preparation, program operation, reviews program's policies and procedures, etc. iii. Consults with radiation oncologists on the physical and radio-biological aspects of patient's

Staff	Roles and responsibilities
	treatments and the development of plans iv. Makes sure that the equipment used in therapy and imaging is working properly and that the machine delivers the right amount of radiation, e.g. performance specification, calibration of the sources, design, development and maintenance of a Quality Assurance program for all treatment modalities, localisation procedures, and computational equipment and programs, etc. v. In charge of facility design and shielding calculations vi. Acquisition and storage of data for treatment plans vii. Calculation of dose distributions and machine settings for patient treatments (dosimetry assurance) viii. Performs “in-vivo” dosimetry for patient treatments ix. Commissioning of diagnostic, planning and treatment equipment and software, e.g. new equipment x. Radiation safety program, e.g. development and administration of the program, compliance with all regulating and certifying agencies xi. Development of techniques to improve the delivery of radiation treatments xii. Supervision of Dosimetrists
Medical Dosimetrist (or just “Dosimetrist”)	i. Works closely with the Radiation oncologist, Medical physicist and Radiation therapist and usually performs duties related to treatment planning and dose calculation ii. Assembles patient data required for dose calculations iii. Calculates (or helps to calculate) and plans the right radiation doses (dose distribution) for

Staff	**Roles and responsibilities**
	each treatment iv. Performs "in-vivo" dosimetry for patient treatments v. Performs periodic checks on treatment records
Radiation oncology nurse (or just "Nurse")	i. A nurse who specialises in radiation oncology ii. Coordinates the patient care and works with the patient, e.g. education, counselling, support for the management of treatment-related side effects, etc.
Radiation therapist (or just "Radiographer")	i. A specialised person who takes X-rays, CT and MRI scans, mammograms, etc. ii. Performs a range of radiographic examinations to produce high-quality images iii. Works with the patient and their family, e.g. provides patient information and support, health advice, etc. iv. Assists other team members in more complex radiological examinations v. Accurate recording and produces reports
Anaesthetist	i. Appropriate pre-operative assessment and preparation during treatment delivery, e.g. in brachytherapy ii. Safe anaesthesia during treatment delivery iii. Care of the patient in the immediate post-operative period
Operating theatre technician (or just "Technician")	i. Prepares and maintains operating theatres and equipment and assist radiation oncology and anaesthetic teams during operations ii. Prepares the patient for treatment, e.g. prepares operating room or operating theatre, sterilises operating room or operating theatre, helps with lifting/moving the patient, helps with patient movement prevention during treatment, etc. iii. Cleans and sterilises operating room or

Staff	Roles and responsibilities
	operating theatre equipment and instruments iv. Helps the team members with gowns and gloves v. Operates sterilisers, lights, etc. and helps to operate some diagnostic equipment vi. Helps to prepare specimens taken for laboratory analysis, etc.

2.2.6 Brachytherapy

The word "Brachy" comes from Greek word "Brakhus" which means short (Merriam-Webster.com 2015). It is referring to "short distance" in terms of short distance between the radiation source and cancerous tumour or targeted tissue.

Brachytherapy is a modality of radiotherapy, which uses an internal radioactive source to kill cancerous cells or to shrink tumours. It has been around since the 1890's (Nath, Anderson et al. 1997), and has progressed ever since. It can deliver the radiation dose to the prostate more precisely than traditional EBRT (Porter, Blasko et al. 1995). In principle, the radiation dose decreases rapidly with distance from source of radiation. Brachytherapy is used to treat early stage cancers and small, localised tumours. Types of brachytherapy are based on their application and are described in Table 2-3 (ASTRO 2014):

Table 2-3 Types of brachytherapy

Type of brachytherapy	Description
Interstitial	Sources are inserted directly into a tumour/target tissue, e.g. prostate, breast, head and neck, etc.
Inter-cavitary (or "Intra-luminal")	Sources are inserted into a body cavity, e.g. vagina, uterus, bronchus, oesophagus
Surface	Sources are placed directly on an external tumour/target surface, e.g. eye, skin, breast, etc.

The two main types of brachytherapy are determined by the intensity of the prescribed radioactive source:

a) High-Dose Rate (HDR) brachytherapy also referred to as "temporary" brachytherapy. Radioactive sources of higher strength are used (usually Iridium-192, or shorter "Ir-192"); the patient's tumour is exposed to such source only for a limited time period (usually a few minutes) over a certain amount of treatments (fractions). The source is inserted and removed via implanted applicator (e.g. catheter, balloon, etc.) remotely via the "afterloader" after every fraction until the overall treatment dose is received. The afterloader is a remotely operated device, which stores the radioactive source. The applicator stays implanted for the duration of the treatment period and is removed after the last treatment, which lasts 1-4 days. HDR brachytherapy is used to treat breast cancer, vaginal cancer, cervical cancer, skin cancer, tongue, head and neck cancer, etc. The dose rate for HDR brachytherapy is >12 Gy/h.

b) Low-Dose Rate (LDR) brachytherapy, also referred to as "permanent" brachytherapy. Radioactive sources of lower strength are used, usually:

a. Iodine-125, or shorter "I-125", which is the most common technique used in Europe (Guedea, Venselaar et al. 2010) and in Ireland; it is used for slow-growing, low-rate tumours (Peschel and Colberg 2003), or
b. Palladium-103, or shorter "Pd-103"; it is used for faster-growing, high-grade tumours (Peschel and Colberg 2003).

These sources can be permanently (e.g. prostate cancer) or temporarily (e.g. neck cancer) implanted directly into the patient's tumour volume (Nath, Anderson et al. 1997). LDR brachytherapy is commonly used to treat prostate cancer, as well as head, neck and throat cancer. The dose rate for LDR brachytherapy is <1 Gy/hour.

Other brachytherapy principles include (the list is not exclusive):

a) Image-Guided Brachytherapy (IGBT): it uses advanced imaging techniques such as CT and MRI to make brachytherapy more precise, safe and effective
b) Pulse-Dose Rate (PDR) Brachytherapy: a modality of HDR brachytherapy which uses sources of intermediate strength and delivers the dose within 1-2 days in 1-2 hourly treatments
c) 4D Brachytherapy: it combines "loose seeds" and "stranded seeds" methods together; both are described in more details in the later chapters.

2.2.7 Low-Dose Rate Brachytherapy

Low-Dose rate (LDR) prostate brachytherapy is used to treat cancer in men with low to intermediate risk of cancer: PSA score and Gleason score above 7 (Barrett, Dobbs et al. 2009; PCF 2015). If two out of three risk factor parameters are present, the patient is selected for the treatment:

a) PSA level >10 ng/ml (based on blood test)
b) Gleason score ≥7 (based on the prostate biopsy)
c) Cancer stage higher than T2b

i. PSA

PSA stands for "Prostate Specific Antigen", and can be found in a blood sample. If PSA > 4 ng/mL, doctors order a prostate biopsy to determine the presence of the cancer (NCI 2012). They also use PSA to test the recurrence of prostate cancer after the prostate cancer treatment (NCI 2012). PSA levels are usually combined with MRI, ultrasound and CT scans to determine the presence of cancerous cells.

ii. Gleason score

Gleason score was developed by a scientist Donald Gleason between 1960 and 1975 and helps with the prognosis of prostate cancer (Patel, Chen et al. 2007). It evaluates details of individual cancer glands and describes the dominant historic grades, from grade 1 (which is well differentiated) to grade 5 (which is very poorly differentiated). The final score is derived by adding the two growth pattern grades together, ranging from 2 to 10 (Barrett, Dobbs et al. 2009; NCI 2014).

iii. Cancer stages

Cancer staging describes the stage of cancer based on the (original) tumour size and the spread of the tumour around the body. It helps with diagnosing the cancer progress (NCI 2015). The "TNM" system is widely used to determine the cancer stage. It is based on the size and the stage of the primary tumour (T), the amount of spread of lymph nodes (N), and the presence of metastasis (M). Table 2-4, Table 2-5, Table 2-6 and Table 2-7 are specific TNM classifications for prostate cancer (Sobin, Gospodarowicz et al. 2011; ACS 2014; NCI 2015):

Table 2-4 Procedures for assessing TNM categories

Category	Description
T	Physical examination, imaging, endoscopy, biopsy, and biochemical tests
N	Physical examination and imaging
M	Physical examination, imaging, skeletal studies, and biochemical tests

Table 2-5 Primary tumour (T)

Primary Tumour (T)	
T1, T2, T3, T4	Size/extent of the primary tumour
T1	Clinically unapparent tumour not palpable or visible by imaging
T1a	Tumour incidental histological finding in 5% or less of tissue resected
T1b	Tumour incidental histological finding in more than 5% of tissue

Primary Tumour (T)	
	resected
T1c	Tumour identified by needle biopsy (e.g. because of elevated PSA)
T2	Tumour confined within the prostate
T2a	Tumour involves one half of one lobe or less
T2b	Tumour involves more than half of one lobe, but not both lobes
T2c	Tumour involves both lobes
T3	Tumour extends through the prostatic capsule
T3a	Extra-capsular extension including microscopic bladder neck involvement
T3c	Tumour invades seminal vesicle(s)
T4	Tumour is fixed or invades adjacent structures other than seminal vesicles; external sphincter, rectum, levator muscles and/or pelvic wall
Tx	Primary tumour cannot be evaluated
T0	No evidence of primary tumour
Tis	Carcinoma In Situ (CIS): abnormal cells are present only in the layer of cells, but have not spread to neighbouring tissue

Table 2-6 Regional Lymph Nodes (N)

Regional Lymph Nodes (N)	
N1, N2, N3, N4	Degree of regional lymph node involvement; number and location of lymph nodes
Nx	Regional lymph nodes cannot be evaluated
N0	No regional lymph node involvement

Table 2-7 Distant Metastasis (M)

Distant Metastasis (M)	
MX	Distant metastasis cannot be evaluated
M0	No distant metastasis
M1	Distant metastasis is present
M1a	Non-regional lymph node(s)
M1b	Bone(s)
M1c	Other site(s)

Stage grouping for prostate cancer is presented in Table 2-8 on the next page (Sobin, Gospodarowicz et al. 2011). These stages are also known as the “clinical” stages. This means the doctor estimates the extent of cancer based on the physical examination, imaging results, blood test and prostate biopsy. Another stage is “pathologic” stage, which is based on the surgery and examination of the removed tissue. The doctor can estimate the extent of the cancer more accurately (the stage of the cancer can therefore change). Both types of staging use the same categories, except T1 which is only used for clinical staging (ACS 2014).

Tumours can also be stratified based on the T-stage, PSA score and Gleason score into three different risk groups as seen in Table 2-9 (Barrett, Dobbs et al. 2009). The risk is higher for an intermediate patient with Gleason score 4+3 rather than 3+4 (Chan, Partin et al. 2000; Barrett, Dobbs et al. 2009; Stark, Perner et al. 2009).

Table 2-8 Stage grouping for prostate cancer

Stage	Category			Gleason score	PSA level
	T	N	M		
Stage I	T1	N0	M0	Gleason score ≤ 6	PSA < 10
	T2a	N0	M0	Gleason score ≤ 6	PSA < 10
Stage II a	T1	N0	M0	Gleason score 7	PSA < 20
	T1	N0	M0	Gleason score ≤ 6	PSA 10 - 20
	T2a or T2b	N0	M0	Gleason score ≤ 7	PSA < 20
Stage II b	T2c	N0	M0	Any Gleason score	Any PSA
	T1, or T2	N0	M0	Any Gleason score	PSA ≥ 20
	T1 or T2	N0	M0	Gleason score ≥ 8	Any PSA
Stage III	T3	N0	M0	Any Gleason score	Any PSA
Stage IV	T4	N0	M0	Any Gleason score	Any PSA
	Any T	N1	M0	Any Gleason score	Any PSA
	Any T	Any N	M1	Any Gleason score	Any PSA

Table 2-9 Tumour stratification for prostate cancer

Risk	T-stage	PSA score	Gleason score
Low	T1 - T2a	< 10	≤ 6
Intermediate	T2b	10-20	7
High	T2c – T4	>20	8 - 10

For example, where cancer stage is higher than T2b, it means that the cancer is present on more than one half, but not both halves of the prostate, with no regional lymph nodes involved and no distant metastasis present. It represents an intermediate risk to the patient, and LDR prostate brachytherapy is one of the recommended cancer treatment options.

2.2.8 Other brachytherapy factors

Other factors are prostate size, shape, pubic arch interference and the swelling of the prostate gland. LDR brachytherapy is more suitable for smaller- to medium- sized prostate with up to 60ml volume (Grimm and Sylvester 2004). Treating larger prostate may be challenging. Sometimes the patient undergoes a hormone therapy to shrink the cancer, prostate gland, and to reduce PSA prior to LDR brachytherapy.

2.2.9 Salvage brachytherapy and boost brachytherapy

If the treatment is combined with other forms of cancer treatment, e.g. EBRT, surgery, or in cases of cancer recurrence (even after a couple of years), “salvage” brachytherapy or “boost brachytherapy” techniques are performed. Both, HDR and LDR brachytherapy techniques can use these two methods. The treatment tasks are the same however, the dose delivered is substantially different.

i. Boost brachytherapy is performed on patients in addition to their (previous) radiation treatment or surgery in intermediate or high-risk cases. It delivers a smaller dose to the prostate gland (approximately 70%), taking into the account the radiation dose received previously, e.g. with EBRT.

ii. Salvage brachytherapy is performed on patients who already received radiation treatment in the past, and have a local cancer recurrence. Similarly to “boost brachytherapy”, salvage brachytherapy delivers a smaller radiation dose to the patient.

2.2.10 The characteristics of “Loose seeds” and “Stranded seeds” Low-Dose Rate brachytherapy techniques

A typical setup of LDR prostate brachytherapy for both, “loose seeds” technique, and “stranded seeds” technique at “Treatment delivery” stage includes stepper, template, Trans-Rectal Ultra-Sound probe connected to the Ultra-Sound with the display and printer, and a computer connected to the Ultra-Sound to provide 2D and 3D feedback of the implanted seeds. After the TRUS probe is inserted into the patient’s prostate gland to provide visual feedback, needles are inserted via the template grid, which is set up on the stepper; seeds are then implanted via the needle handled by the Radiation oncologist.

The goal of both techniques is to achieve the prescribed dose throughout the prostate gland. They are very accurate and efficient procedures for prostate cancer treatment. The following two techniques are applied in Ireland:

- “Loose seeds” technique (also referred to as the “individual” brachytherapy technique): the radioactive seeds are preloaded in a stainless steel cartridge, and inserted individually through the template grid fixed on the stepper via the needle by using the Mick® applicator (Radio-Nuclear Instruments, Inc., Mount Vernon, NY). Mick® applicator is a specifically designed medical instrument for accurate seed implantation in the prostate gland. It allows for seed placement adjustability and seed spacing during the LDR brachytherapy treatment. The implanted “loose” seeds tend to migrate around the prostate gland and around the body (Grimm and Sylvester 2004; Pawlicki, Dunscombe et al. 2010).

- “Stranded seeds” technique: the radioactive seeds are connected together with biodegradable material; the strand is inserted through the needle inserted into the patient’s gland via the template grid without the Mick® applicator; the implanted seeds have lower seed migration than the “loose seed” technique (Grimm and Sylvester 2004; Reed, Wallner et al. 2007; Saibishkumar, Borg et al. 2009).

2.2.11 Advantages and disadvantages of Low-Dose Rate prostate brachytherapy

a) Patient’s perspective

Advantages:

- One-off procedure (it may require an overnight stay in some hospitals)
- Short treatment time (approximately 90 minutes)
- Short recovery time
- Short half-time of the implanted radioactive seeds (approximately 60 days)
- Unaffected fertility
- Low rate of major complications
- No hormone therapy
- No risk of harming family or friends with radiation

Disadvantages:

- Anaesthetic is used for the treatment
- Radioactive seeds stay permanently implanted in the patient’s body
- Implanted radioactive seeds can move or migrate around the prostate gland or body if they are not implanted correctly
- Urinal dysfunction after the treatment, e.g. more frequent urination, feeling pain while urinating, etc.; in rare cases a complete blockage of urination (in such cases catheter is required for a short term)
- Erectile dysfunction and ejaculation discomfort after the treatment
- Mild pain, tenderness, soreness, bruising or bleeding in the perineum for a few days after the treatment
- It is not recommended to drive a vehicle immediately after the procedure due to fatigue and pain medications
- It is not recommended to be around pregnant women and young children straight after the treatment

b) Hospital's perspective

Advantages:

- Quick application (approximately 90 minutes for seed implantation)
- Short half-life for I-125 (approximately 60 days) and Pd-103 (approximately 17 days)
- Highly skilled and well trained staff
- A well-established technique
- Low treatment costs

Disadvantages:

- The radiation seed implantation procedure requires strict protocols and Quality Assurance
- A team of experts required at the same time for the treatment; if one team member is not present, the treatment cannot go ahead
- For the team members it may take time to learn the tasks and to perform them independently e.g. 6-8 months for Radiation oncologist, 6-12 months for Medical physicist, etc
- Possible seed migration within the prostate gland (it may not have a major effect on the patient's health and healing process)
- Radiation protection measures for the team and the patient, e.g. wearing personal protective equipment
- Issues with automation and automated equipment
- High costs of replacement of hardware and software equipment if faulty, e.g. ultrasound, Mick® applicator, etc.

2.2.12 Safety issues within radiotherapy

Worldwide, about 32 million nuclear medicine procedures are carried out annually, and from 10 million patients per year, 10% receive radiotherapy treatment. The International Action Plan for the Radiological Protection of Patients report indicates that the number of patients will increase in the following years (International Atomic

Energy Agency 2002). According to the Towards Safer Radiotherapy report by the Royal College of Radiologists et al. (2008) in the UK, 181 incidents affecting 338 patients were reported between May 2000 and August 2006. It means that three patients out of 100,000 treatments in Radiotherapy are opened to incidents (The Royal College of Radiologists, Society and College of Radiographers et al. 2008).

However, the system may be considered safe, but errors within the system can still occur. The potential for error in radiotherapy is high according to the "To Err is Human: Building a Safer Health System" report by Kohn et al. (2000), who reported that most errors occurred at the "Planning" stage and the "Treatment delivery" stage in EBRT, and at the "Treatment delivery" stage in brachytherapy (Kohn, Corrigan et al. 2000). There are many levels at which incidents can occur. The occurrence is typically a consequence of an error appearing somewhere in the system. Error can be caused by humans, system, or by the interaction between the two at different levels and at different stages of the working process. The likelihood of events to happen varies, as well as their consequences. In extreme cases, the consequence cannot only be a severely damaged or wounded patient, but the death of a patient being treated. One example was an incident at Glasgow hospital, where a patient was severely overdosed during the radiotherapy treatment due to human error, receiving 58% more radiation than intended (Williams 2007). Similar accidents happened in the United States where in one case, a patient received radiotherapy treatment to the wrong areas of the body (brain and neck instead of tongue), and in another case, a patient received up to three times higher radiation dose than planned. The consequences were fatal in both cases (Bogdanich 2010a). Similar cases were reported in France, where patients died because of radiation overdose due to a number of different reasons, such as miscalculation, miscommunication, types of, or lack of wedges, errors in simulation, software updates, misadministration (Derreumaux, Etard et al. 2008), among others. However, based on the data collected between 1976 and 2007 by World Health Organisation, death due to radiation dose toxicity only involved 1% of the whole patient population (WHO 2008; Bogdanich 2010a; Bogdanich 2010b; Bogdanich 2010c).

2.2.13 Safety approach towards radiotherapy

Following a series of articles in New York Times by Bogdanich (Bogdanich 2010a; Bogdanich 2010b; Bogdanich 2010c), who critiqued the quality of delivered radiation treatments, and provided a number of case studies, Food and Drug Administration (FDA) analysed the data from Medical Device Reports (MDRs), collected between December 2009 and February 2010. "A letter to Manufacturers of Linear Accelerators, Radiation Therapy Treatment Planning Systems, and Ancillary Devices", published in April 2010, outlined that out of 1,182 errors reported by MDRs, 74% of the errors were connected with the use of linear accelerators, and that the most frequent errors occurred were caused by software issues, use of device, and improper display (Shure 2010).

2.2.14 Practical use of human reliability and human error analysis methods in the healthcare environment

Dhillon (2003) wrote that humans are a "*critical component of the healthcare system*", and that based on the report by Kohn et al. (2000), human error is still a prevalent source of deaths in health care. He presented an overview of 9 human reliability and error analysis techniques that are applicable to the health care environment: Failure Modes and Effect Analysis (FMEA), Root Cause Analysis (RCA), Fault Tree Analysis (FTA), Cause and Effect Diagram (CAED), Hazard Operability Study (HAZOP), Probability tree method, Error-Cause Removal Program (ECRP), Man-Machine Systems Analysis (MMSA), and the Markov method. The background to each method was provided, as well as the main steps, benefits, drawbacks, and examples (Dhillon 2003). Despite good presentation, the methods were not critiqued. Also there was no information provided about the 'Healthcare FMEA™' (HFMEA™), which was developed a few years earlier by the US Department of Veteran Affairs specifically for the healthcare environment (DeRosier, Stalhandske et al. 2002).

2.2.15 Systems safety approach – Radiotherapy risk assessments

Fallon *et al.* (2009) reported that the previous research showed there was a complete absence of the application of systems engineering at the development stage of the radiotherapy system (Fallon, Chadwick et al. 2009). There was a need for systems engineering approach towards the risk from the Human Factors Engineering perspective. Risk assessment in radiotherapy was performed by the authors to determine to what extent the risk was to patient safety in the management of patient medical records of softcopy and hardcopy mediums. Also to what extent the current information systems supported current standards and best practice (Fallon, Chadwick et al. 2009). Different methods were used for data collection, such as information flows, observations and interviews. IDEFØ model was used to complete hazard analysis of patient files, and the Health Service Executive (HSE) Risk Assessment Tool was used for conducting the Risk assessment. The Risk assessment results were calculated based on the matrix of the likelihood of the occurrence and severity of occurrence, and presented as a "Total Risk Score" (Fallon, Chadwick et al. 2009). Health Failure Mode and Error Analysis (HFMEA™) was used to determine the structure of the hazardous events and how to make the radiotherapy environment safer. The authors found that there were similarities between the radiotherapy system and the engineering system. However, the emphasis of their research was on data collection and not on the process improvement. There was an overlap of manual data input in some of the processes (e.g. data input occurred twice), as well as difficult retrieval of the data from databases. Interestingly, the authors discovered that no job design or human factors methods were used previously between users and technology, as well as no systems safety methods for healthcare risk assessments. The authors also pointed out that team work plays a significant role in radiotherapy despite heavy regulations of the healthcare environment (Fallon, Chadwick et al. 2009).

2.2.16 Legislation

Legislation helps countries with guiding and governing their policies issued by their government and the European Union (EU). EU issues Regulations, Directives and acts on a number of different topics, including radiation protection safety, radioactive sources, ionising and non-ionising radiation, as well as transport of radioactive sources. It is the duty of each member country to implement EU Directives so that they become a law. The purpose of a law is to protect the individual's rights. There are three types of law in Ireland: constitutional law, which can only be amended by a referendum, statue law, passed by the Government Ministers under the power conferred on them of Acts, and common law, which applies to the civil law. The EU law is comprised of primary legislation, e.g. treaties between the governments of Member states, secondary legislation, e.g. EU Regulations, Directives, Decisions, Recommendations, and case law, e.g. judgments of the European Court of Justice. Every action by the EU is founded on treaties approved voluntarily by all EU member countries. The following are two lists of selected legislation related to radiotherapy, and in particular, to brachytherapy in Ireland and in the EU (in chronological order):

a) Irish legislation:

- S.I. No. 125/2000 - Radiological Protection Act, 1991 (Ionising Radiation) Order, 2000
- S.I. No. 478/2002 - European Communities (Medical Ionising Radiation Protection) Regulations 2002
- Radiological Protection (Amendment) Act, 2002
- S.I. No. 116/2003 - European Communities (Classification, Packaging, Labelling and Notification of Dangerous Substances) Regulations 2003
- S.I. No. 62/2004 - European Communities (Classification, Packaging and Labelling of Dangerous Preparations) Regulations 2004
- S.I. No. 875/2005 - Radiological Protection Act 1991 (Control of High-Activity Sealed Radioactive Sources) Order 2005
- S.I. No. 25/2006 - European Communities (Classification, Packaging,

Labelling and Notification of Dangerous Substances) (Amendment) Regulations 2006

- S.I. No. 299 of 2007 - Safety, Health and Welfare at Work (General Application) Regulations 2007
- S.I. No. 303/2007 - European Communities (Medical Ionising Radiation Protection) (Amendment) Regulations 2007
- S.I. No. 732 of 2007 - Safety, Health and Welfare at Work (General Application) (Amendment) Regulations 2007
- S.I. No. 459/2010 - European Communities (Medical Ionising Radiation Protection) (Amendment) Regulations 2010
- S.I. No. 349/2011 - European Communities (Carriage of Dangerous Goods by Road and Use of Transportable Pressure Equipment) Regulations 2011
- S.I. No. 291 of 2013 Safety, Health and Welfare at Work (Construction) Regulations 2013

It is important to highlight that The Office of Radiological Protection (ORP) are in charge of matters relating to the road transport of radioactive materials of the "European Agreement concerning the International Carriage of Dangerous Goods by Road" (ADR) Class 7, issuing licences, etc. It also "regulates to protect workers and members of the public from the harmful effects of exposure to all ionising radiation" (HSE n.d.). Health and Safety Executive, however, regulates patient radiation protection practices in private and public radiological facilities. This includes regulating patient safety, e.g. "protecting patients from the harmful effects of exposure to ionising radiation" (HSE n.d.).

b) EU legislation

- Directive 80/836/Euratom on Ionising radiation (1980)
- Council Regulation (Euratom) No 1493/93 of 8 June 1993 on shipments of radioactive substances between Member States
- Directive 2003/122/Euratom - Radioactive sources
- Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation (EC) No 1907/2006

- The European Communities (Carriage of Dangerous Goods by Road and Use of Transportable Pressure Equipment) Regulations (S.I. No. 349 of 2011)
- Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation
- Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards - General Safety Requirements Part 3 (2014)
- European Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR) (2015)

Chapter 3: Mapping the Low-Dose Rate Prostate Brachytherapy Treatment Process

3.1 Chapter overview

This chapter introduces a mapping approach to 'Low-Dose Rate' brachytherapy "Treatment delivery" process. After initial literature review and general familiarisation with the treatment process, observational period identified the User-System interaction between core team members and the technologies, and developed and validated the Hierarchical Task Analysis. The main operations identified in Hierarchical Task Analysis were later on used in assessing the perceived workload.

3.2 Introduction

It was important to successfully map the observed working process in order to understand it from the engineering perspective: to identify the LDR prostate brachytherapy treatment process stages, with particular focus on the "Treatment delivery" stage, who are the core team members involved at each stage, how they perform their tasks, and how they interact with each other and the technologies they are using. For this reason, an observational Human-Interaction method and Hierarchical Task Analysis method, a variant of Task Analysis were developed to map the LDR prostate brachytherapy treatment process. LDR prostate brachytherapy treatment is described in more detail in Section 2.2.7. Furthermore, the characteristics of "loose seeds" and "stranded seeds" LDR prostate brachytherapy are described in more detail in Section 2.2.10.

3.3 Methods

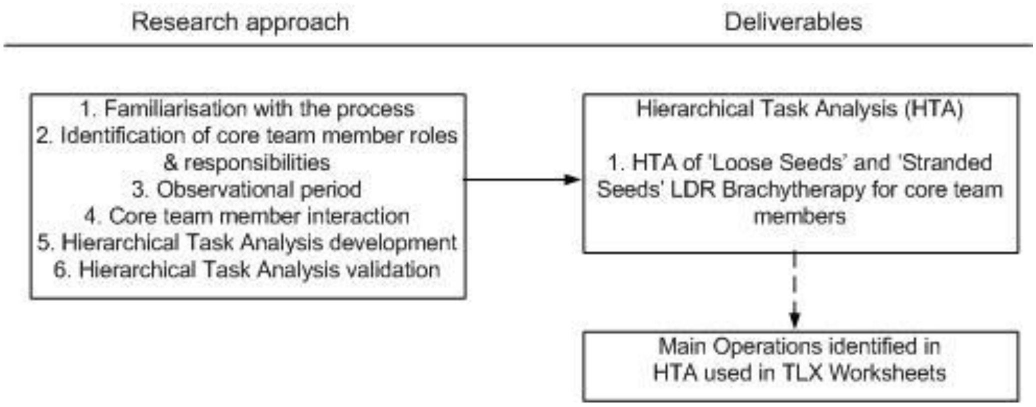
A structured approach for mapping the LDR prostate brachytherapy is presented in Figure 3-1 included:

- Familiarisation with the process;
- Identifying the core team members and responsibilities;
- Observational period:

- Identifying the stages
- Identifying team roles and the technology
- Mapping user-system interaction
- Task Analysis and Hierarchical Task Analysis
- The development and validation of Hierarchical Task Analysis.

The main stages of mapping the LDR prostate therapy treatment process after the familiarisation and the process, and identifying the team roles and responsibilities was the observational stage, in which user-system interaction was mapped, and Hierarchical Task Analysis method was used to map the process. The main operations identified during the observational stage were used in the data collection of the perceived workload described in more detail in the next chapter The methods used for mapping the LDR treatment process are described in more detail in the following sub-sections.

Figure 3-1 Methodical approach to mapping the Low-Dose Rate brachytherapy treatment process



3.3.1 Familiarisation with the process

The initial literature review gave a detailed overview of the LDR prostate brachytherapy treatment process (AAPM 1993; Nath, Biggs et al. 1994; Nath, Anderson et al. 1997; Khan 2003). In particular it gave an understanding and familiarity with the treatment process objectives, general and specific roles and responsibilities of the core team members. In order to understand the objectives of this treatment process from the point of view of human interaction with the technology, the familiarisation had to be followed by an observational period.

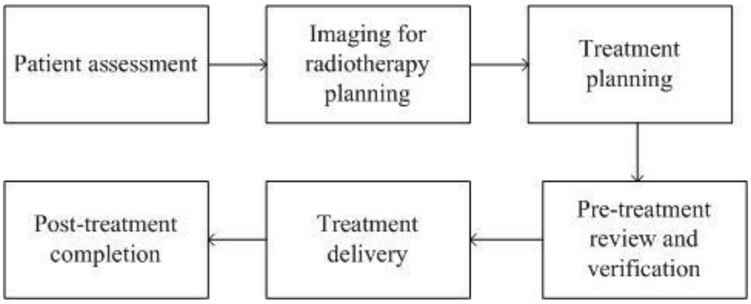
3.3.2 Observational period

Thirty two LDR prostate brachytherapy treatment cases were observed during the observational period. From the Human Factors Engineering perspective, the focus was on identifying the stages of the treatment process, the core team members and their interaction, and to map the process in a systematic manner. The observation was done during the LDR prostate brachytherapy treatment process in real clinical environments, strictly without interrupting or interference with the treatment process itself.

3.3.3 The stages

The LDR prostate brachytherapy stages in this research matched the stages mapped by Ford et al. (2012):

Table 3-1 Low-Dose rate brachytherapy stages



The LDR prostate brachytherapy stages are described in more detail in Table 3-3.

3.3.4 The core team

At the "Treatment delivery" stage of LDR prostate brachytherapy the patient is anesthetised. While the patient is anaesthetised, the core team performs their operations and sub-operations (often referred to as "tasks" and "sub-tasks") to deliver the treatment. The core team at this stage consisted of:

- Radiation oncologist
- Medical physics team, including Dosimetrists; in this research, Medical physicists were often referred to as “Medical physicist #1” and “Medical physicist #2” because of their distinctive roles
- Radiation oncology nurse (often referred to as “Nurse”)
- Anaesthetist
- Radiologist (only at selected hospitals)

The role of the Dosimetrist was normally complimenting the role of the Medical physicist, and was regarded as the same role as Medical physicist during the observed “Treatment delivery” stages.

Additional team members were also present in the operating theatres at times, especially at the beginning and at the end of the treatment procedure, e.g. Operating theatre technicians and staff nurses. They helped with the set-up and preparation of the operation theatre, lifting the patient, cleaning and disinfecting the instruments, discarding the waste, etc. However, they did not play a vital role during the “Treatment stage” of LDR prostate brachytherapy, and were therefore not included in the research.

3.3.5 Team roles and the technology

Team roles and the technology used in LDR brachytherapy using “loose seeds” technique and “stranded seeds” technique were mapped out. Besides observation and taking notes, informal interviews were used, as well as feedback and questions and answers to and from the individual core team members. Team roles fit the American Association of Physicists in Medicine (AAPM) guidelines (AAPM Task Group 56) (Nath, Anderson et al. 1997).

A list of equipment used in LDR brachytherapy was assembled based on the observation and feedback from the individual core team members and is presented in Table 3-4.

3.3.6 User-system interaction at the LDR prostate brachytherapy

A user-system interaction was mapped out during the observation of thirty two "Treatment delivery" cases prior to data collection. Besides observation, questions and answers and informal interviews were performed, and feedback was given from the individual core team members about the operations and sub-operations performed during the "Treatment delivery" stage for both, "loose seeds" and "stranded seeds" LDR brachytherapy.

The complexity of the user-system interaction is presented in User-system interaction diagram of "loose seeds" LDR prostate brachytherapy setupFigure 3-3 and Figure 3-4. The particular focus of this observation was to understand the user-device interaction, visual feedback, and verbal interaction, that is person-to-person communication patterns. In terms of operations and sub-operations, both LDR prostate brachytherapy techniques were mapped out in detail by using the Hierarchical Task Analysis technique.

3.3.7 Task Analysis

In Merriam-Webster online dictionary (Merriam-Webster.com 2015), *task* is defined as:

"A piece of work that has been given to someone: a job for someone to do".

Analysis is defined as (Merriam-Webster.com 2015):

"1. A careful study of something to learn about its parts, what they do, and how they are related to each other
2. An explanation of the nature and meaning of something"

Combining both words, "Task Analysis" can therefore simply be explained as "a careful study of work components someone performs". Task analysis describes, evaluates, analyses and assesses a range of techniques performed by the human operators in human-machine systems and is a crucial step in evaluating and designing systems (Kirwan and Ainsworth 1992; Karwowski 2007). It studies the action the operator is required to do ("the goal") and presents all the steps (or "operations") necessary to reach this goal (e.g. operations and sub-operations) in a structural way. Each task should be meaningful; it should be associated with the goal and identifiable by the user. Task Analysis is designed to optimise human performance and to reduce the potential for errors (Kirwan and Ainsworth 1992).

3.3.8 Hierarchical Task Analysis

Hierarchical Task Analysis (HTA) is "the best known task analysis technique to represent the relationship between tasks and subtasks" (Kirwan and Ainsworth 1992). It has been in use for more than thirty years (Stanton 2006). It is a goal-oriented technique used to assess worker's tasks and subtasks in the order they are carried out and can also document other information, e.g. the persons performing the tasks, availability and cost of materials involved, time spent on the tasks, equipment provided, staff preferences, etc.

HTA has been initially used for training, and has also been applied to interface design, error predictions, safety performance, allocation of functions, workload assessments, inspections, etc. (Kirwan and Ainsworth 1992; Hollnagel 2003; Stanton 2006; Karwowski 2007). It has been applied in petro-chemical industry, nuclear industry, aviation, healthcare, military, etc. (Hollangel 2003; Stanton, Hedge et al. 2004; Karwowski 2007). It is valuable also in perceived workload research because it can investigate whether the person has the capacity to perform the task reliably (Karwowski 2007).

The objective of Hierarchical Task Analysis is to present the main task (or the "main goal", or "input") the person (who is often referred to as the "operator") has to achieve, hierarchically, followed by decomposition of subsequent tasks and subtasks underneath the main goal (also referred to as "actions") and goal indications (also referred to as "feedback"). Each task and subtask is specified as a "goal" itself and is often referred to as sub-ordinate goal, or "sub-goal". The actions required to achieve the goals are called "operations". The operations and sub-operations are broken down to the level of single individual tasks, which contribute to the main goal.

HTA can also include specific statements or conditions, which specify the order of the performed operations:

i. "Plans" or "Rules", which are the conditions under which the actions are carried out, e.g. "Do step one first, then second, third, etc.", "Do task in any order", "Wait for this task first, then do the other task", "Repeat until this task is reached", etc.
ii. "Selective rules" or "Decisions", e.g. "In case one do this, in case two do that".

HTA can be presented in a form of a list, table and/or a diagram, with the main goal/task on top, followed by the appropriately numbered operations and sub-operations below. An example of HTA for operations performed by the "Medical physicist #1" at the "Treatment delivery" stage is presented in Figure 3-2.

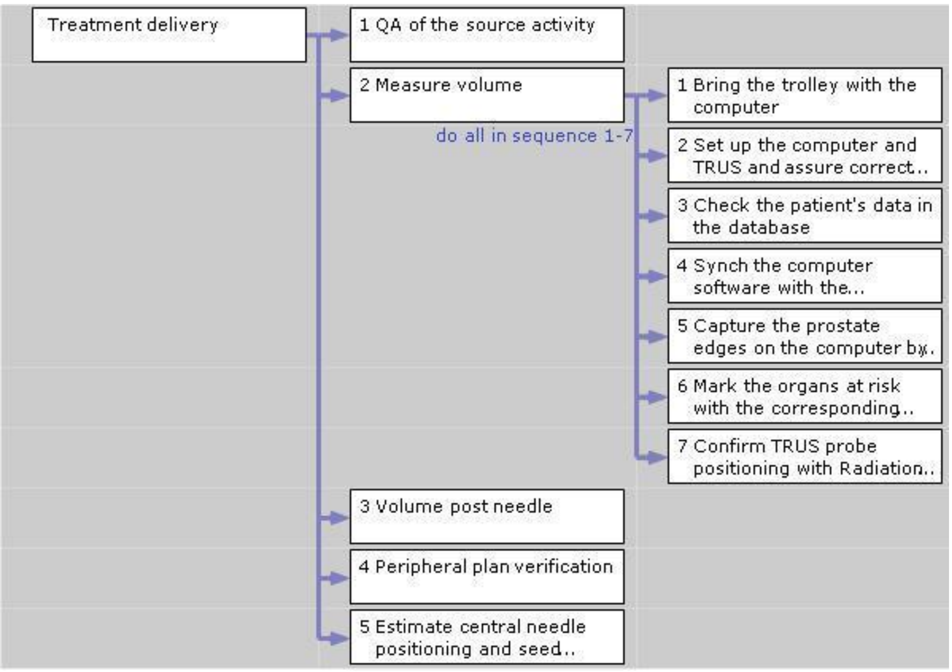


Figure 3-2 An example of HTA diagram for some of the operations and sub-operations performed by Medical physicist at the "Treatment delivery" stage of "loose seeds" LDR brachytherapy

To create a successful HTA, Stanton proposed the following steps (Karwowski 2007):

1. Define the purpose of the analysis
2. Define the boundaries of system description
3. Assess a variety of resources of the system to be analysed
4. Describe the system goals and sub-goals
5. Keep the number of immediate sub-goals to a small number (between 3 and 10)
6. Link goals to sub-goals and describe the conditions under which the sub-goals are triggered
7. Stop redescribing the sub-goals when the analysis is fit-for-purpose
8. Verify the analysis with external experts
9. Be prepared to revise the analysis.

A similar set of structural steps have been proposed by Hollangel (2003) and Stanton et al. (2004).

The development and validation of Hierarchical Task Analysis at the “Treatment delivery” stage of LDR prostate brachytherapy

Hierarchical Task Analysis (HTA) was developed at the “Treatment delivery” stage for both, “loose seeds” and “stranded seeds” LDR prostate brachytherapy. The following HTA guidelines were followed (Stanton, Hedge et al. 2004; Karwowski 2007):

i. The purpose and the boundaries

The purpose of HTA was to understand, map and present the operations and sub-operations performed by core team members at the “Treatment delivery” stage of LDR prostate brachytherapy.

ii. The stakeholders

The stakeholders were the core team members who were closely involved in the "Treatment delivery" stage (listed above).

iii. The selection of the operation goals and sub-goals

The selected operation goals were observed together with the individual team members. They were based on the standard operating procedures of each hospital site separately and previous work done by Chadwick (2010) and Ford *et al.* (2012), among others. Interestingly, because one hospital site pioneered the "loose seeds" technique in Ireland, all other hospitals which adopted the same technique, also had the same operation goals. On the other hand, the hospital site which used "stranded seeds" technique had a slightly different set of operation goals, specific to their technique.

iv. Data collection

Data on operation goals and sub-goals was collected based on the observation of approximately 60 cases of LDR prostate brachytherapy in the clinical hospital environment. The data was based on the researcher's notes and on non-formal conversations with the individual team members who were performing the operations during these cases. The data is presented in the table format in the Results section in this thesis.

v. Data validation

The individual team members from all hospital sites involved in this research validated the HTA data by reviewing the HTA diagrams of the "Treatment delivery" stage of the LDR prostate brachytherapy.

3.4 Results

This section presents the results based on mapping the “Treatment delivery” stage LDR brachytherapy treatment process. Results for team roles and responsibilities are presented, as well as detailed description of “Treatment delivery” LDR brachytherapy stage, a list of technology used in “loose seeds” and “stranded seeds” LDR prostate brachytherapy, user-system interaction, a detailed list of HTA stages for each core team member in “Stranded seed” and “Loose seed” LDR prostate brachytherapy treatment, a list of brachytherapy data collected during the “data collection” period (e.g. prostate volume, average number of seeds and needles inserted, etc.), and observational notes of issues raised during the “data collection” period (e.g. prostate gland volume, asymmetry, pubic arch interference, applicator, etc.).

3.4.1 Team roles and responsibilities

Each team member has their own role and responsibilities at the “Treatment delivery” stage of LDR prostate brachytherapy. The team consists of Radiation oncologists, Medical physics team, Medical dosimetrists (also referred to as “Dosimetrists”), Radiation oncology nurse (also referred to as “Nurse”), Anaesthetists, and Operating theatre technicians (also referred to as “Technicians”). Knowing the team member’s roles was part of the mapping the LDR prostate brachytherapy process. An example of team roles in LDR prostate brachytherapy treatment is presented in Table 3-2.

Table 3-2 An example of staff roles and responsibilities in LDR prostate brachytherapy

Staff	Roles and responsibilities
Radiation oncologist	i. A consultant medical doctor who specialises in treating cancer patients using radiotherapy ii. Sees referred patients who are scheduled to receive radiotherapy for cancer treatment iii. Determines the exact field or area to be treated by

Staff	Roles and responsibilities
	radiation and prescribe the number of treatments needed iv. Plans review and approval of cancer treatment v. Performs the treatment vi. Monitors the treatment vii. Follows up the patient
Medical Physicist	i. A radiation expert who helps to plan the treatment with the radiation therapy team ii. Plans for resource allocation with Radiation oncologists, administrators and technologists, e.g. equipment usage, selection and replacement of equipment, budget preparation, program operation, reviews program's policies and procedures, etc., including ordering seeds for LDR brachytherapy iii. Consults with Radiation oncologists on the physical and radio-biological aspects of patient's treatments and the development of plans iv. Makes sure that the equipment used in therapy and imaging is working properly, e.g. performance specification, calibration of the sources, design, development and maintenance of a Quality Assurance program for all treatment modalities, localisation procedures, and computational equipment and programs, etc. v. In charge of facility design and seed calibration vi. Performs "in-vivo" dosimetry for patient treatments vii. Commissioning of diagnostic, planning and treatment equipment and software, e.g. software updates and upgrades viii. Radiation safety program, e.g. development and administration of the program, compliance with all regulating and certifying agencies ix. Development of techniques to improve the delivery of radiation treatments x. Supervision of dosimetrists xi. Follow up of the patient, e.g. 30-day check-up, dose delivery, etc.

Staff	Roles and responsibilities
Medical Dosimetrist (or just "Dosimetrist")	i. Works closely with the Radiation oncologist, Medical physicist and Radiation therapist and usually performs duties related to treatment planning and dose calculation ii. Assembles patient data required for dose calculations iii. Calculates (or helps to calculate) and plans the right radiation doses (dose distribution) for each treatment iv. Performs "in-vivo" dosimetry for patient treatments v. Performs periodic checks on treatment records
Radiation oncology nurse (or just "Nurse")	i. A nurse who specialises in radiation oncology ii. Coordinates the patient care and works with the patient, e.g. education, counselling, support for the management of treatment-related side effects, etc.
Radiographer	i. A specialised person who takes X-rays, CT and MRI scans, mammograms, etc. ii. Performs a range of radiographic examinations to produce high-quality images iii. Works with the patient, e.g. provides patient information and support, health advice, etc. iv. Assists other team members in more complex radiological examinations v. Records results accurately and produces reports
Anaesthetist	i. Appropriate pre-operative assessment and preparation during treatment delivery, e.g. in brachytherapy ii. Safe anaesthesia during treatment delivery iii. Care of the patient in the immediate post-operative period
Operating theatre technician (or just "Technician")	i. Prepares and maintains operating theatres and equipment and assists radiation oncology and anaesthetic teams during operations ii. Prepares the patient for treatment, e.g. prepares operating room or operating theatre, sterilises the operating room or operating theatre, helps with lifting/moving the patient, helps with patient movement prevention during treatment, etc. iii. Cleans and sterilises operating room or operating

Staff	Roles and responsibilities
	theatre equipment and instruments iv. Helps the rest of the team members with gowns and gloves v. Operates sterilisers, lights, etc. and helps to operate some diagnostic equipment vi. Helps to prepare specimens taken for laboratory analysis, etc.

3.4.2 Low-Dose Rate brachytherapy stages

Low-Dose Rate (LDR) brachytherapy treatment stages from Table 3-1 are presented in more details in Table 3-3. American Association of Physicists in Medicine (AAPM) Report #61 is an important publication to refer to. It provides recommendations for brachytherapy treatment; it provides the definition and responsibilities of the Medical physicist in brachytherapy, it makes recommendations for brachytherapy team members, defines team functions, instrumentation needed for the treatment, etc. (Nath, Anderson et al. 1997).

Table 3-3 Low-Dose Rate brachytherapy treatment stages

Stage	Description
Patient assessment	• Patient is assessed and diagnosed by the Radiation oncologist based on their symptoms, lab results, physical examination, tumour stage, tumour extent, etc. • Consideration of guidelines and patient wishes • Diagnosis and protocol decision
Imaging for radiotherapy planning	• Patient is positioned correctly; reference points and guides are marked • CT, MRI, X-ray and/or ultrasound imaging is performed to determine the exact location of the patient’s tumour, tumour size to be treated • Images are exported to the cancer treatment database

Stage	Description
Treatment planning	• Contouring: after the images are reviewed, cancerous cells are highlighted and dose volume is predetermined
Pre-treatment review and recommendation	• The plan is reviewed by the Radiation oncologist and other radiotherapy staff, e.g. Medical physicists, Dosimetrists, etc. • Optimal plan for cancer treatment is recommended and confirmed • Radioactive seeds are ordered based on the approved treatment plan
Treatment delivery	• The planned dose is delivered as a one-off treatment (LDR brachytherapy) using TRUS • Team work is necessary
Post-treatment completion	• Confirmation of treatment delivery • CT scan performed after 30-days • Patient has a consultation with the Radiation oncologist about their treatment and the possible side effects • Patient follow-up as agreed with Radiation oncologist

It has to be noted that an additional external stage could be added to LDR brachytherapy treatment process, called "Equipment and software quality management", where daily, weekly and monthly QA of the cancer treatment devices is performed, including software updates.

3.4.3 The technology

A list of equipment used by the Radiation oncologist, Radiologist (only in "stranded seeds" brachytherapy), and Medical physics team at the "Treatment delivery" stage of "loose seeds" and "stranded seeds" LDR prostate brachytherapy is presented in Table 3-4. Please note that "NA" was applied where the equipment was not used.

The list is not exclusive.

For a more detailed understanding of the whole set up, it was important to identify what equipment was used at the "Treatment delivery" stage, who were the team members interacting with the equipment, and who interacted with whom individually and in a team. For this purpose, a visual user-system interaction drawing was developed during the research for both, "loose seeds" brachytherapy and "stranded seeds" LDR brachytherapy. The user-system diagrams Figure 3-3 and Figure 3-4 show the complexity of the "Treatment delivery" stage, when the patient is anesthetised, and the structure of the team working under time pressure to perform the tasks successfully and with least errors. The interactions comprised of machine-interaction and personal (team) interaction: user-device interaction, visual feedback and person-to-person communication patterns.

Table 3-4 A list of equipment used in LDR prostate brachytherapy

Equipment	Loose seeds	Stranded seeds
TRUS probe	✓	✓
Ultrasound display and controls	✓	✓
Mick® applicator	✓	NA
Computer with display and specialised software	✓	✓
Printer	✓	✓
Stepper	✓	✓
Template grid	✓	✓
Needles	✓	✓
Seed cartridges	✓	NA
Seed strands	NA	✓
Calibration chamber	✓	✓
Geiger-Müller (G-M) counter	✓	✓
Radioactive badge	✓	✓
Radiation Personal Protective Equipment, e.g. lead apron	NA	✓

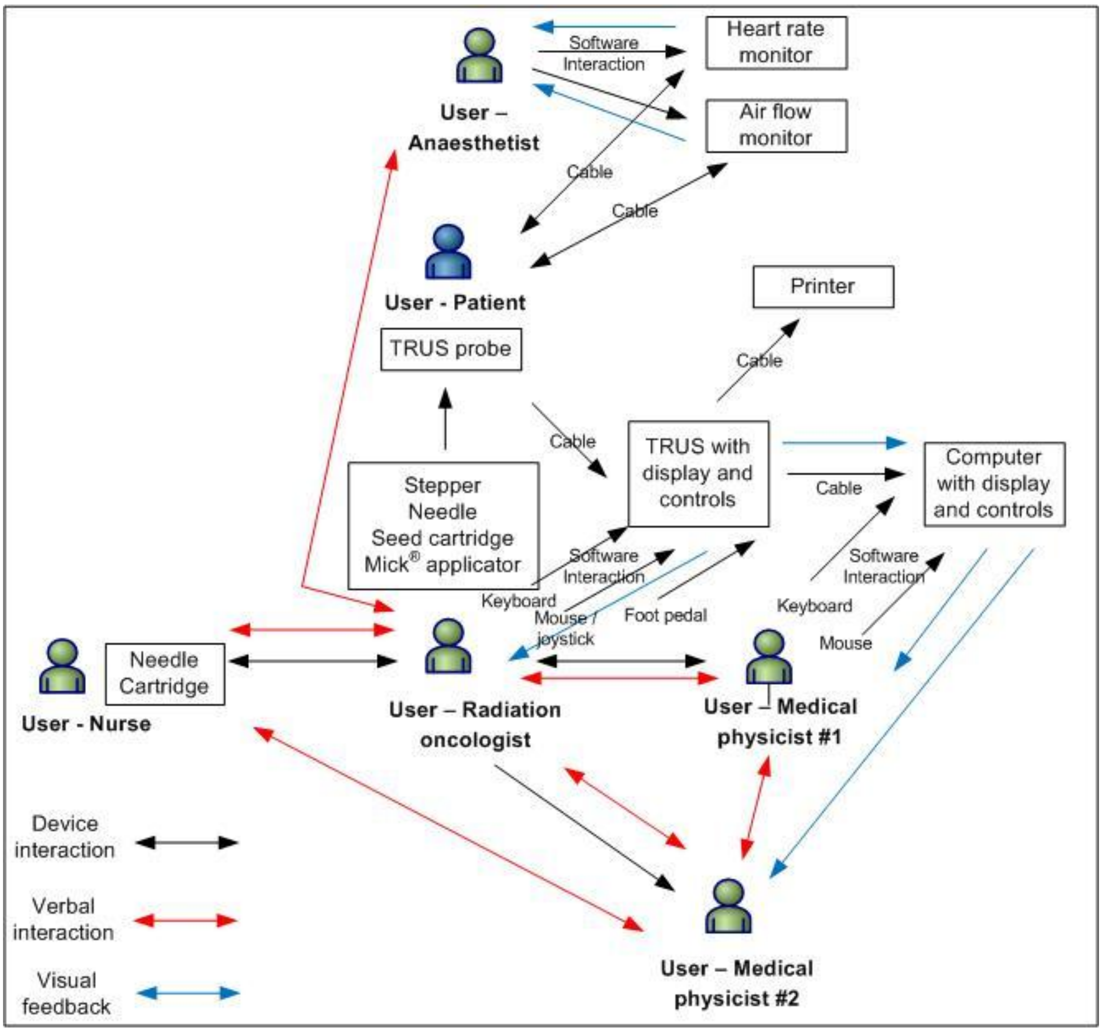


Figure 3-3 User-system interaction diagram of "loose seeds" LDR prostate brachytherapy setup

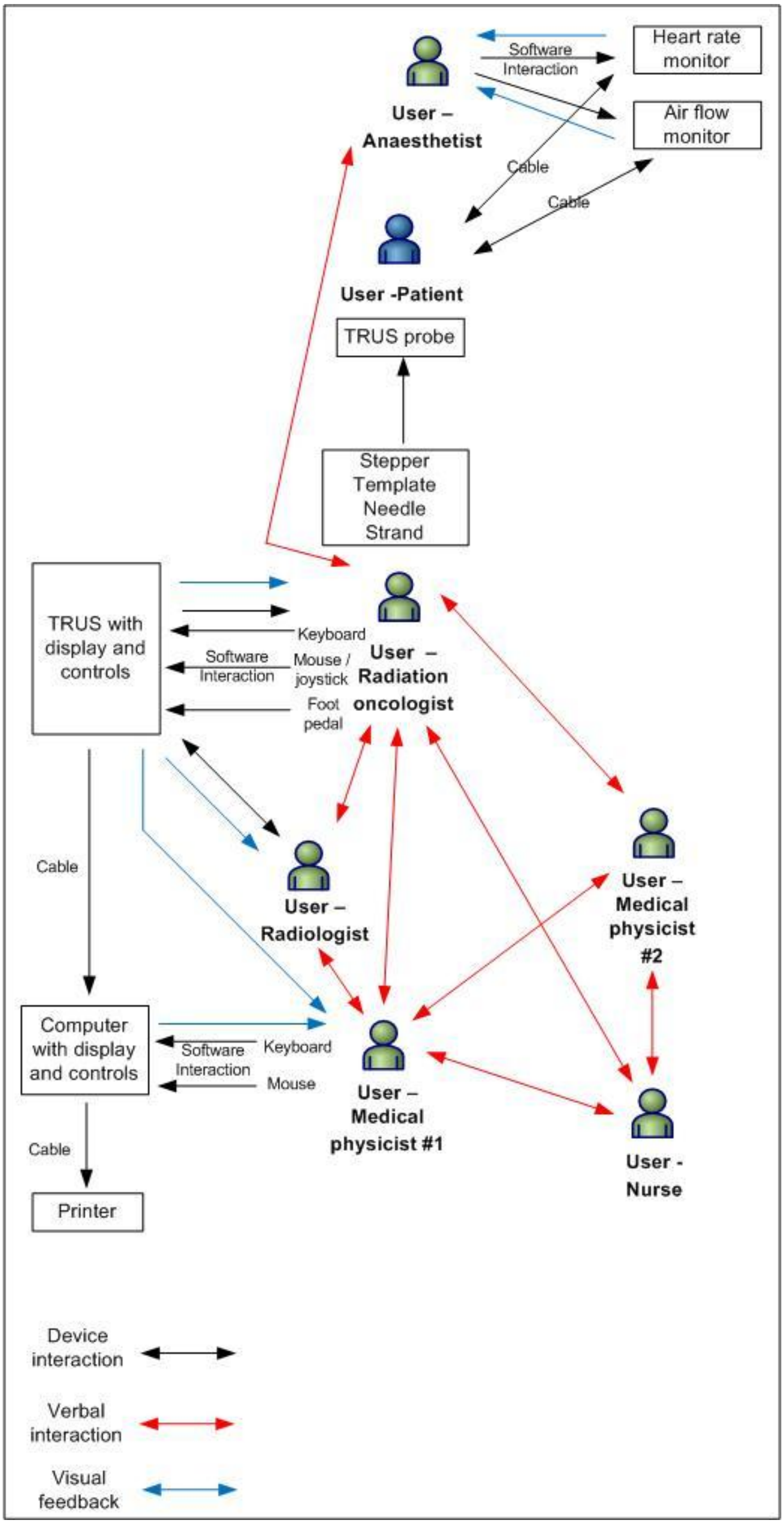


Figure 3-4 User-system interaction diagram of "stranded seeds" LDR prostate brachytherapy setup

3.4.4 Hierarchical Task Analysis

During the initial observation period of thirty two Low-Dose Rate (LDR) prostate brachytherapy cases, a detailed Hierarchical Task Analysis (HTA) was developed for every team member's operation at the "Treatment delivery" stage of the LDR prostate brachytherapy cancer treatment. The "operations" are actions performed by the human operator in order to achieve the goal; "subsequent operations", or "sub-operations" are actions performed by the human operator in order to fulfil the "operation". The main operations identified in Hierarchical Task Analysis presented below, were later on used in assessing the perceived workload. A more detailed HTA that expands on the main HTA operations into a number of sub-operations is presented after the section with the main operations on page 77.

Note that the emphasis was on identifying operations and sub-operations of the core team members:

- Radiation oncologist
- Medical physics team (often referred to as "Medical physicist #1" and "Medical physicist #2")
- Radiation oncology nurse
- Anaesthetist
- Radiologist (in some hospitals)

Also note that some of the sub-operations performed by Medical physicists were sometimes performed by Dosimetrists, and were in HTA still assessed and referred to as "Medical physicist" because the operations and sub-operations they performed were the same.

The main Low-Dose Rate prostate brachytherapy operations

The main LDR prostate brachytherapy operations identified in Hierarchical Task Analysis are presented below for each core team member and for each type of LDR prostate brachytherapy: “Loose seeds” and “stranded seeds” LDR prostate brachytherapy. These main operations were used for the assessment of perceived workload, presented in the next chapter of this thesis.

i. Main HTA operations at “loose seeds” LDR prostate brachytherapy technique

Radiation oncologist

Table 3-5 Loose seeds LDR brachytherapy: Main HTA operations of Radiation oncologist

Operation number	Operation description
1	TRUS placement
2	Measure volume
3	Needle implantation / insertion
4	Volume post needle
5	Virtual prostate and urethra positioning
6	Peripheral seeding and planning
7	Central seeding and planning
8	Volume post implant *

* Only performed in one hospital site

Medical physicist #1

Table 3-6 Loose seeds LDR brachytherapy: Main HTA operations of Medical physicist #1

Operation number	Operation description
1	QA of the source activity
2	Measure volume
3	Volume post needle
4	Peripheral plan verification

Operation number	Operation description
5	Estimate central needle positioning and seed implantation
6	Final verification (Dosimetry)
7	Room monitoring / contouring – no source left

Medical physicist #2

Table 3-7 Loose seeds LDR brachytherapy: Main HTA operations of Medical physicist #2

Operation number	Operation description
1	QA of the source activity*
2	Room monitoring / contouring – no source left *
3	Seeds evaluation form

*The order of the operations matches and compliments the operations performed by Medical physicist #1

Radiation oncology nurse

Table 3-8 Loose seeds LDR brachytherapy: Main HTA operations of the Radiation oncology nurse

Operation number	Operation description
1	Patient setup
2	Seeding

Anaesthetist

Table 3-9 Loose seeds LDR brachytherapy: Main HTA operations of Anaesthetist

Operation number	Operation description
1	Patient setup
2	Patient monitoring

ii. Main HTA operations at "stranded seeds" LDR prostate brachytherapy

Radiation oncologist

Table 3-10 Stranded seeds LDR brachytherapy: Main HTA operations of Radiation oncologist

Operation number	Operation description
1	Catheter and ultrasound positioning
4	Assess plan
5	Seed placement
7	Assess implant (+/- extra seeds)

Radiologist

Table 3-11 Stranded seeds LDR brachytherapy Main HTA operations of Radiologist

Operation number	Operation description
2	Refine the position, volume study & image acquisition
3	Contouring
6	Seed placement
7	Assess implant (+/- extra seeds)

Medical physicist #1

Table 3-12 Stranded seeds LDR brachytherapy: Main HTA operations of Medical physicist #1

Operation number	Operation description
1	Equipment setup & patient data
2	Volume study
3	Plan & plan printing
4	Real time check
5	Final plan verification (Dosimetry)

Medical physicist #2

Table 3-13 Stranded seeds LDR brachytherapy: Main HTA operations of Medical physicist #2

Operation number	Operation description
1	Prepare the needles, seed calibration & prepare the seeds
2	Room monitoring – no source left

Radiation oncology nurse

Table 3-14 Stranded seeds LDR brachytherapy: Main HTA operations of the Radiation oncology nurse

Operation number	Operation description
1	Patient setup & TRUS setup
2	Needle loading report

Anaesthetist

Table 3-15 Stranded seeds LDR brachytherapy: Main HTA operations of Anaesthetist

Operation number	Operation description
1	Patient setup
2	Patient monitoring

Hierarchical Task Analysis of Low-Dose Rate prostate brachytherapy operations and sub-operations

Hierarchical Task Analysis in this section expanded the main operations identified above into more detail. As well as the main operations, it also included a number of sub-operations for each core team member, for each type of LDR prostate brachytherapy: “Loose seeds” and “stranded seeds” LDR prostate brachytherapy. Due to space constrictions, HTA is presented only in a table format.

i. Main operations and sub-operations of the "loose seeds" LDR prostate brachytherapy technique

Radiation oncologist

Table 3-16 Task Analysis of operations and sub-operations performed by Radiation oncologist at the "Treatment delivery" stage of "Loose seeds" LDR prostate brachytherapy

Operator: Radiation oncologist			
Technique: Loose seeds			
Main task: Treatment delivery			
Plan: Do all in one sequence; do optional if applicable			
Operation number	**Operation description**	**Sub-operation number**	**Detailed sub-operation description**
1	TRUS placement	1.1	Wash and disinfect hands & put on cap, shoe covers, gloves, surgical gown and mask
		1.2	Set up the TRUS
		1.3	Set up the stepper
		1.4	Set up the disposable needle template grid on the stepper
		1.5	Prepare the TRUS (apply the condom and the gel)
		1.6	Place TRUS probe into the patient
		1.7	Acquire image on the ultrasound display
		1.8	Adjust the patient and/or TRUS to acquire good image (avoid pubic arch interference) (optional)
		1.9	Once set, calibrate with the computer
2	Measure volume	2.1	Call out TRUS positioning planes in 0.5cm intervals
		2.2	Contour the prostate: mark each prostate slice on TRUS to measure overall prostate volume
		2.3	Call out the prostate volume presented on ultrasound display to

			Medical physicist #1
		2.4	Print out each TRUS plane on TRUS printer
3	Needle implantation / insertion	3.1	Decide on the treatment plan for needle and seed insertion with Medical physicist #1 and Medical physicist #2
		3.2	Confirm the treatment plan for needle and seed insertion once decided
		3.3	Insert peripheral needles as per treatment plan
		3.4	Call out needle positioning to Medical physicist #1 and #2
4	Volume post needle	4.1	Mark the prostate slice on TRUS to measure overall prostate volume after the needle implantation
		4.2	Read out the volume post needle implantation
5	Virtual prostate and urethra positioning	5.1	Perform urethral catheterisation on the patient (use gel, saline, syringe, gloves, catheter, etc.)
		5.2	Highlight the urethra on the TRUS display for Medical physicist #1
		5.3	Confirm virtual prostate and urethra positioning with Medical physicist #1
6	Peripheral seeding and planning	6.1	Adjust the seed positioning based on the number of needles inserted with Medical physicist #1 for optimal isodosis by using the virtual 3D model (equal radiation intensity to the area (optional)
		6.2	Insert seeds via peripheral needles positioned as per treatment plan
		6.3	Call out the position of each needle and the number of seeds implanted to Medical physicist #1 and #2 and to the Nurse
		6.4	Review virtual seeds implanted and

			3D virtual prostate model on computer display together with Medical physicist #1 to determine best seed positioning (optional)
7	Central seeding and planning	7.1	Insert seeds via central needles positioned as per treatment plan
		7.2	Call out the position of each needle and the number of seeds implanted to Medical physicist #1 and #2 and to the Nurse
		7.3	Insert additional needle(s) with seeds if necessary (optional)
		7.4	Call out the position of the additional needle and the number of seeds implanted to Medical physicist #1 and #2 and to the Nurse (optional)
		7.5	Review 3D model of virtual prostate on computer display together with Medical physicist #1
		7.6	Remove the needles
		7.7	Remove the TRUS probe *
		7.8	Dispose the needle template grid *
		7.9	Remove the stepper *
		7.10	Disassemble the bed *
		7.11	Remove surgical gown, gloves, mask, cap, shoe covers & wash and disinfect hands *
		7.12	Sign the seed evaluation form *
8	Volume post implant **	8.1	Mark the prostate slice on TRUS to measure overall prostate volume after the needle implantation and to check for oedema
		8.2	Read out volume post seed implant to Medical physicists
		8.3	Remove the needles
		8.4	Remove the TRUS probe
		8.5	Dispose the needle template grid
		8.6	Remove the stepper
		8.7	Disassemble the bed

		8.8	Remove surgical gown, gloves, mask, cap, shoe covers & wash and disinfect hands
		8.9	Sign the seed evaluation form

** Only for sites who do not perform the 8th operation*
*** Only performed at one hospital site*

Medical physicist #1

Table 3-17 Task Analysis of operations and sub-operations performed by Medical physicist #1 at the "Treatment delivery" stage of "Loose seeds" LDR prostate brachytherapy

Operator: Medical physicist #1			
Technique: Loose seeds			
Main task: Treatment delivery			
Plan: Do all in one sequence; do optional if applicable			
Operation number	**Operation description**	**Sub-operation number**	**Detailed sub-operation description**
1	QA of the source activity	1.1	Take the seed cartridges out of the storage
		1.2	Check the number of seeds and number of cartridges
		1.3	Check the manufacturer's seed strength
		1.4	Calibrate the seeds:
		1.4.1	Use dosimeter to measure seed strength
		1.4.2	Use calculator to confirm the overall seed strength and possible seed strength deviation
		1.4.3	Confirm the calculations with Medical physicist #2
2	Measure volume	2.1	Bring in the trolley with the computer
		2.2	Set up the computer and TRUS and assure correct connectivity and visual feedback

		2.3	Check the patient's data in the database
		2.4	Synch the computer software with the ultrasound image (grid setup: check the grid, grid corners, etc.)
		2.5	Capture the prostate edges on the computer by following what Radiation oncologist marked on ultrasound (with red colour)
		2.6	Mark the organs at risk with the corresponding colours: white (prostate), green (urethra) and blue (rectum)
		2.7	Confirm TRUS probe positioning with Radiation oncologist
3	Volume post needle	3.1	Check the contouring and prostate volume and adjust if necessary
		3.2	Read out the prostate volume to Radiation oncologist and Medical physicist #2
		3.3	Calculate the number of needles and seeds needed for treatment plan with Medical physicist #2 (use pen, paper, and the calculator)
		3.4	Decide on the number of seeds and needles implanted together with Medical physicist #2 and Radiation oncologist
		3.5	Refer to the AAPM needle/seed guidelines if necessary
4	Peripheral plan verification	4.1	Follow Radiation oncologist's seed implantation by inserting virtual seeds into the computer program
		4.2	In vivo dosimetry: Check and verify the isodosis of the implanted seeds and the dose in critical organs (ongoing)
5	Estimate central needle positioning and seed implantation	5.1	Check the virtual model of prostate with the seed implantation to show the dose distribution for optimal

			needle/seed implantation with Radiation oncologist
		5.2	Present the 3D virtual model of prostate with the seed implantation to show the dose distribution
		5.3	Follow Radiation oncologist's seed implantation by inserting virtual seeds on the dosimetry system (computer software)
		5.4	In vivo dosimetry: Check and verify the isodosis of the implanted seeds and the dose in critical organs (ongoing)
6	Final verification (dosimetry)	6.1	Present the 3D virtual model of prostate with the seed implantation to show the dose distribution
		6.2	Confirm the 3D virtual model with Radiation oncologist
		6.3	Present the 2D transverse view to Radiation oncologist
		6.4	Save all the work on computer and switch it off
7	Room monitoring / contouring – no source left	7.1	Check the Geiger-Müller (G-M) counter performance
		7.2	Swipe the whole room with G-M counter to check for any radioactive sources, e.g. loose/lost I-125 seeds
		7.3	Store the G-M counter

Medical physicist #2

Table 3-18 Task Analysis of operations and sub-operations performed by Medical physicist #2 at the "Treatment delivery" stage of "Loose seeds" LDR prostate brachytherapy

Operator: Medical physicist #2			
Technique: Loose seeds			
Main task: Treatment delivery			
Plan: Do all in one sequence; do optional if applicable			
Operation number	**Operation description**	**Sub-operation number**	**Detailed sub-operation description**
1	QA of the source activity	1.1	Check the number of cartridges and number of seeds
		1.2	Check the manufacturer's seed strength
		1.3	Calibrate the seeds:
		1.3.1	Use dosemeter to measure seed strength
		1.3.2	Use calculator to confirm the overall seed strength and possible seed strength deviation
		1.3.3	Confirm the calculations with Medical physicist #1
2	Room monitoring / contouring – no source left		Use the G-M counter to scan for a radioactive source around the patient and in the operating theatre, e.g. loose/lost I-125 seeds:
		2.1	Check the G-M counter performance
		2.2	Scan the whole room with the G-M counter
		2.3	Store the G-M counter
3	Seeds evaluation form	3.1	Calculate the number of needles and seeds needed for treatment plan with Medical physicist #1
		3.2	Confirm the number of needles implanted by following the Radiation oncologist, the Nurse

			and Medical Physicist #1
		3.3	Draw the needle positioning on the evaluation form
		3.4	Confirm the number of seeds implanted with the Radiation oncologist and Nurse
		3.5	Draw the seed positioning on the evaluation form
		3.6	Check the needle positioning and seed implantation (ongoing task)
		3.7	Use G-M counter to check the cartridge when empty (optional – unless Nurse does not do it)
		3.8	Write down the needle prostate volume
		3.9	Calculate the number of seeds implanted and total dose delivered to the patient
		3.10	Give the evaluation form to Radiation oncologist to sign

Nurse

Table 3-19 Task Analysis of operations and sub-operations performed by the Nurse at the "Treatment delivery" stage of "Loose seeds" LDR prostate brachytherapy

Operator: Nurse			
Technique: Loose seeds			
Main task: Treatment delivery			
Plan: Do all in one sequence; do optional if applicable			
Operation number	**Operation description**	**Sub-operation number**	**Detailed sub-operation description**
1	Patient setup	1.1	Escort the patient into the operating theatre (patient is brought in either on a wheelchair or on a separate hospital bed)
		1.2	Prepare the patient's bed (e.g. clean the bed, fit the bed sheet, prepare

			the bed features, etc.)
		1.3	Set up the patient on the bed (lift the patient, position the patient and patient's legs, cover the patient, empty the patient's bowel and remove clinical waste)
		1.4	Prepare the bed features, Mick® applicator, needles, seed cartridges, cartridge holder, catheter, gel, syringe, saline, antiseptic, etc.
		1.5	Insert saline into syringe for Radiation oncologist
		1.6	Adjust the patient bed for Radiation oncologist to acquire better image on TRUS display (optional)
2	Seeding	2.1	Set up the table, table lamp, chair, cartridge holder, gloves, etc.
		2.2	Prepare the cartridges on a cartridge holder
		2.3	Fix the cartridge onto the Mick® applicator
		2.4	Insert gel into the patient's urethra
		2.5	Count the number of seeds left in the cartridge
		2.6	Call out the number of the seeds (to Radiation oncologist and Medical physicist #2)
		2.7	Change cartridge when empty:
		2.7.1	Remove it from the applicator
		2.7.2	Place it on the table
		2.7.3	Pick up the new cartridge
		2.7.4	Insert the new cartridge into the applicator
		2.7.5	Discard the needles into the container (check them first with G-M counter (optional); Medical physicist #2 can check them instead)
		2.8	Discard the cartridge when empty into the container (check them first with G-M counter (optional); Medical

			physicist #2 can check them instead)
		2.9	Adjust the table lamp (optional)
		2.10	Clean, disinfect and pack away the Mick® applicator at the end
		2.11	Remove the waste container at the end
		2.12	Escort the patient out to the recovery room after the treatment

Anaesthetist

Table 3-20 Task Analysis of operations and sub-operations performed by Anaesthetist at the "Treatment delivery" stage of "Loose seeds" LDR prostate brachytherapy

Operator: Anaesthetist			
Technique: Loose seeds			
Main task: Treatment delivery			
Plan: Do all in one sequence; do optional if applicable			
Operation number	**Operation description**	**Sub-operation number**	**Detailed sub-operation description**
1	Patient setup	1.1	Check the equipment (e.g. breathing system, flow-meters, medical gases, etc.)
		1.2	Prepare drugs (e.g. the amount of drug, syringe, etc.)
		1.3	Check the patient's ID
		1.4	Talk to the patient (check for allergies, etc.)
		1.5	Attach essential monitors to the patient (e.g. heart rate monitor, gas/agent monitor, arterial pressure monitor, etc.)
		1.6	Establish intravenous access (i.e. infusion directly into the vein)
		1.7	Anaesthetise the patient (general anaesthesia)
		1.8	Secure patient's pathway (optional)
		1.9	Cover patient's eyes (optional)

		1.10 1.11	Attach additional monitors (optional) Commence additional monitoring (optional)
2	Patient monitoring	2.1 2.2 2.3 2.4 2.5	Maintain anaesthesia (e.g. monitor the patient's heart rate, air flow and arterial pressure, change intravenous bags, adjust anaesthetic concentration, etc.) Discontinue anaesthesia (e.g. discontinue drug administration, administer reversal drugs, administer 100% oxygen) Wake up the patient after the treatment Escort the patient to the recovery room Complete documentation (e.g. check details on anaesthetic chart, check post-operative care instructions, file documentation)

ii. Main operations and sub-operations of the "loose seeds" LDR prostate brachytherapy technique

For a better understanding, a timeline of operations performed by Radiation oncologist & Radiologist, and Medical physicist #1 & Medical physicist #2 are presented in Figure 3-5. Their operations were interchanging, that is why they are numbered differently to other operations in this chapter. For example, Radiation oncologist performed operation 1, after that the Radiologist performed operations 2 and 3, and then Radiation oncologist operation 4, and so on. This way the flow of operations was kept together.

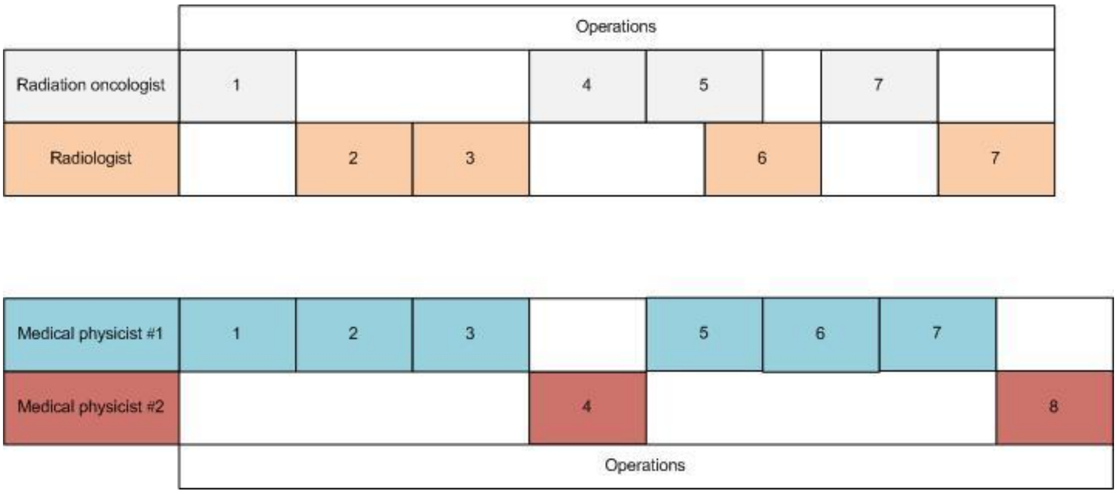


Figure 3-5 A presentation of operation timeline for operations performed by Radiation oncologist & Radiologist, and Medical physicist #1 & Medical physicist #2 of "Stranded seeds" LDR prostate brachytherapy

Radiation oncologist

Table 3-21 Task Analysis of operations and sub-operations performed by Radiation oncologist at the "Treatment delivery" stage of "Stranded seeds" LDR prostate brachytherapy

Operator: Radiation oncologist			
Technique: Stranded seeds			
Main task: Treatment delivery			
Plan: Do all in one sequence; do optional if applicable			
Operation number	**Operation description**	**Sub-operation number**	**Detailed operation description**
1	Catheter placement & ultrasound positioning	1.1 1.2	Prepare the gel, syringe and catheter Acquire image on the ultrasound display
4	Assess plan	4.1 4.2 4.3	Assess the pubic arch interference (if necessary insert test needles at the outer limits of the prostate and await confirmation from Medical Physicist #1) Re-adjust patient's leg position (optional) Assess the treatment plan on the

			number of seeds and needles implanted
		4.4	Adjust TRUS probe if necessary
		4.5	Put on lead apron
5	Seed placement	5.1	Check the template grid, patient position, TRUS probe position, virtual TRUS and computer feedback and adjust if necessary
		5.2	Check the printed plan
		5.3	Check for zero rotation with Medical physicist #1
		5.4	Listen to the nurse calling out the number of needles & stranded seeds that need to be implanted
		5.5	Take out the prepared needle with the inserted strand from the needle box
		5.6	Check the needle and strand position with the Radiologist and Medical physicist #1 before implant
		5.7	Insert the needle with the stranded seeds in the correct position via the grid based on the Nurses' call out (by using the "top down" approach) and by following the visual feedback on TRUS display and computer display (repeat for each needle as per treatment plant)
		5.8	Remove the empty needle after the strand is implanted
		5.9	Discard the empty needle once it has been used into the sharps bin
7	Assess implant	7.1	Assess the implanted seeds with the Radiologist and Medical physicist #1 on the computer
		7.2	Insert additional seeds if necessary (optional)
		7.3	Check 3D model of implanted seeds with Radiologist and Medical physicist on the computer

		7.4 7.5	Remove the TRUS probe after the assessment Take off the lead apron and store it

Radiologist

Table 3-22 Task Analysis of operations and sub-operations performed by Radiologist at seed the "Treatment delivery" of "Stranded seeds" LDR prostate brachytherapy

Operator: Radiologist			
Technique: Stranded seeds			
Main task: Treatment delivery			
Plan: Do all in one sequence; do optional if applicable			
Operation number	**Operation description**	**Sub-operation number**	**Detailed operation description**
2	Refine the position, volume study & image acquisition	2.1 2.2 2.3 2.4 2.5	Place TRUS probe into the patient Perform urethral catheterisation on the patient (use gel, saline, syringe, gloves, catheter, etc.) Call out of the TRUS probe positioning on TRUS display to Medical physicist #1 (for synchronisation) Perform prostate volume study on the computer by using TRUS software Adjust TRUS probe if necessary (optional)
3	Contouring	3.1 3.2 3.3	Mark the organs at risk with the corresponding colours: white (prostate), blue (rectal wall) Mark the urethra position after the gel is inserted with green colour (organ at risk) Read out the prostate volume shown on computer display

6	Seed placement	6.1 6.2 6.3 6.4	Put on lead apron Listen to the Nurse calling out the number of needles and seeds that need to be implanted Adjust TRUS probe for optimal visual feedback if necessary (by using lateral and vertical views) Check the seed implantation on the TRUS display and the computer display
7	Assess implant	7.1 7.2 7.3	Assess the implanted seeds with the Radiation oncologist and Medical physicist #1 on the computer Check virtual 3D model of implanted seeds with Radiation oncologist and Medical physicist #1 Take off the lead apron and store it

Medical physicist #1

Table 3-23 Task Analysis of operations and sub-operations performed by Medical physicist #1 at the "Treatment delivery" stage of "Stranded seeds" LDR prostate brachytherapy

Operator: Medical physicist #1			
Technique: Stranded seeds			
Main task: Treatment delivery			
Plan: Do all in one sequence; do optional if applicable			
Operation number	**Operation description**	**Sub-operation number**	**Detailed operation description**
1	Equipment setup & patient data	1.1 1.2	Bring in the trolley with the computer, printer and the cable connections Set up the computer, printer, TRUS and assure correct connectivity, visual feedback and synchronisation (confirm the alignment of the needle against the

			needle in the software)
		1.3	Open the software (VariSeed)
		1.4	Create the patient data in the software
2	Volume study	2.1	Follow the call out of the TRUS probe by Radiation oncologist and capture images
		2.2	Check the contouring and prostate volume against the live image
3	Plan & plan printing	3.1	Prepare a treatment plan based on the isodose distribution (the number of strands and seeds inserted)
		3.2	Decide on the number of seeds and needles to be implanted
		3.3	Print out two copies of the plan via the printer once the plan is ready / accepted (one for Radiation oncologist and one for Medical physicist #2)
4	Real time check	4	N/A
5	Seed placement & needle positioning	5.1	Put on lead apron
		5.2	Follow seed implantation on the computer display and on the TRUS display (adjust if necessary)
		5.3	Implant virtual seed via the software (based on the implanted strand with the seeds by the Radiation oncologist)
		5.4	Check the isodoses of the implanted seeds (ongoing)
6	Final plan verification (Dosimetry)	6.1	Assess the implanted seeds with the Radiation oncologist and Radiologist on the computer
		6.2	Present 3D model of implanted seeds to Radiation oncologist and Radiologist
		6.3	Take off the lead apron and store it

Medical physicist #2

Table 3-24 Task Analysis of operations and sub-operations performed by Medical physicist #2 at the "Treatment delivery" stage of "Stranded seeds" LDR prostate brachytherapy

Operator: Medical physicist #2			
Technique: Stranded seeds			
Main task: Treatment delivery			
Plan: Do all in one sequence; do optional if applicable			
Operation number	**Operation description**	**Sub-operation number**	**Detailed operation description**
1	Prepare the needles, seed calibration & prepare the seeds	1.1	Put on gloves, lead apron and glasses
		1.2	Take out the seeds from the container
		1.3	Measure the activity of the seeds (check the seed activity and seed strength) by using dosemeter
		1.4	Store the seeds back in the container
		1.5	Prepare the needles by plugging the open end with bone wax
		1.6	Cut the number of seeds based on the printed plan by using needle cutting block and scalpel
		1.7	Insert the prepared needle containing seeds into the needle box
		1.8	Take off the gloves, lead apron and glasses and store them
2	Room monitoring		Use the G-M counter to scan for a radioactive source around the patient and in the operating theatre, e.g. loose/lost I-125 seeds:
		2.1	Check the G-M counter performance
		2.2	Scan the whole room with the G-M counter
		2.3	Store the G-M counter

Nurse

Table 3-25 Task Analysis of operations and sub-operations performed by the Nurse at the "Treatment delivery" stage of "Stranded seeds" LDR prostate brachytherapy

Operator: Nurse			
Technique: Stranded seeds			
Main task: Treatment delivery			
Plan: Do all in one sequence; do optional if applicable			
Operation number	**Operation description**	**Sub-operation number**	**Detailed operation description**
1	Patient setup & TRUS setup	1.1	Prepare the stepper and setup the disposable needle template grid
		1.2	Prepare the patient's bed (e.g. clean/sterilise the bed; prepare the bed sheet, etc.)
		1.3	Escort the patient into the operating theatre
		1.4	Setup and position the patient correctly (e.g. position the patient's legs)
		1.5	Cover the patient with sterile theatre drapes
		1.6	Prepare the stepper, disposable needles, template grid and TRUS probe
		1.7	Apply condom and gel on the TRUS probe
		1.8	Fit the printed plan onto a visible position for Radiation oncologist, Radiologist & Medical physicist #2
		1.9	Adjust the lights in the operating theatre if necessary
		1.10	Remove the template grid after the assessment
		1.11	Clean and decontaminate the instruments
2	Needle loading report	2.1	Put on lead apron
		2.2	Call out the number of seeds and

			needles that need to be implanted to Radiation oncologist and Radiologist based on the printed plan
		2.3	Take off the lead apron and store it

Anaesthetist

Table 3-26 Task Analysis of operations and sub-operations performed by Anaesthetist at the "Treatment delivery" stage of "Stranded seeds" LDR prostate brachytherapy

Operator: Anaesthetist			
Technique: Stranded seeds			
Main task: Treatment delivery			
Plan: Do all in one sequence; do optional if applicable			
Operation number	**Operation description**	**Sub-operation number**	**Detailed sub-operation description**
1	Patient setup	1.1	Check the equipment (e.g. breathing system, flow-meters, medical gases, etc.)
		1.2	Prepare drugs (e.g. the amount of drugs, syringe, etc.)
		1.3	Check the patient's ID
		1.4	Talk to the patient (check for allergies, etc.)
		1.5	Setup and position the patient correctly
		1.6	Establish intravenous access (i.e. infusion directly into the vein)
		1.7	Anaesthetise the patient (general anaesthesia)
		1.8	Escort the patient into the operating theatre (patient is already on the bed)
		1.9	Attach essential monitors to the patient (e.g. heart rate monitor, gas/agent monitor, arterial pressure monitor, etc.)
		1.10	Secure patient's pathway (optional)
		1.11	Cover patient's eyes (optional)

		1.12	Attach additional monitors (optional)
		1.13	Commence additional monitoring (optional)
2	Patient monitoring	2.1	Put on lead apron
		2.2	Maintain anaesthesia (e.g. monitor the patient's heart rate, air flow and arterial pressure, change intravenous bags, adjust anaesthetic concentration, etc.)
		2.3	Discontinue anaesthesia (e.g. discontinue drug administration, administer reversal drugs, administer 100% oxygen)
		2.4	Take off lead apron after the treatment
		2.5	Wake up the patient
		2.6	Escort the patient to the recovery room
		2.7	Complete documentation (e.g. check details on anaesthetic chart, check post-operative care instructions, file documentation)

3.4.5 Summary of Hierarchical Task Analysis operations and sub-operations

Table 3-27 Summary of Hierarchical Task Analysis operations and sub-operations at the "Treatment delivery" stage of "Loose seeds" and "Stranded seeds" LDR brachytherapy

Core team member	Loose seeds		Stranded seeds	
	Operations	**Sub-operations**	**Operations**	**Sub-operations**
Radiation oncologist	7 (8) *	40 (47) *	4	21
Radiologist	/	/	4	15
Medical physicist #1	7	29	6	16
Medical physicist #2	3	16	2	11
Radiation oncology nurse	2	18	2	14
Anaesthetist	2	16	2	20
Total	22	126	16	97

* Only performed in one hospital site

3.5 Discussion

The discussion section follows the structure of the results section. In this section, the key findings are presented, the main research stages are discussed, including the LDR prostate brachytherapy stages, core team roles and responsibilities, and the discussion on Hierarchical Task Analysis for "Loose seeds" and "Stranded seeds" LDR prostate brachytherapy. The chapter concludes with research limitations and future recommendations for practice.

3.5.1 The main findings of this chapter

The main findings of this chapter were identifying team roles and responsibilities of the core team members at the treatment delivery of the LDR prostate brachytherapy treatment, identifying the stages of LDR prostate brachytherapy treatment process, and especially focussing on the 'Treatment delivery' stage of LDR prostate brachytherapy treatment. The core team member's roles match the AAPM guidelines on ‘Code of Practice’ (AAPM 1993; Meigooni 1995; Nath, Anderson et al. 1997) in terms of core team member’s competencies, roles and responsibilities, personnel requirements, equipment requirements, safety procedures, etc. Furthermore, the technology used in LDR prostate brachytherapy was researched for both, ‘Loose seeds’ and ‘Stranded seeds’ LDR prostate brachytherapy, and the user-system interaction with the technologies. The role of each core team member was mapped in detail by using HTA in a systematic manner, identifying main operations and their sub-operations for each core team member separately. The summary of HTA operations and sub-operations is presented in Table 3-27.

3.5.2 The main Low-Dose Rate brachytherapy process mapping stages

Thirty two LDR treatment cases were observed to study, understand and to map the LDR prostate brachytherapy process. The objectives were to:

a. Identify the LDR brachytherapy treatment stages, to identify the core team members, their roles and responsibilities, and the technologies used in the “loose seeds” technique and “stranded seeds” technique.
b. Understand the interaction between the users and technologies; as a result, user-system interaction diagrams were drawn for both LDR brachytherapy techniques.
c. Identify the main key operations and sub-operations of the core team members. The main operations were written down, and subsequently all of the sub-operations as well. Besides the observation and taking notes, informal interviews were used, as well as feedback from the individual core team members.
d. Produce Hierarchical Task Analysis for a structured, broad and detailed overview for both, “loose seeds” and “stranded seeds” brachytherapy.

Based on the observation, and with the help of the core team members, during the development of Hierarchical Task Analysis, six main LDR brachytherapy operations were identified:

1. Patient assessment
2. Imaging
3. Treatment planning
4. Pre-treatment review and verification
5. Treatment delivery
6. Post-treatment completion.

The “Treatment delivery” stage was selected as the main focus of this research, because it involved the patient itself, the core LDR brachytherapy team performing the treatment, and “high end” technologies, or “automation” which is used to successfully perform this treatment. The main operations identified with the Hierarchical Task Analysis at the “Treatment delivery” stage were later on used in assessing the perceived workload.

3.5.3 The core team roles and responsibilities

Eight roles and responsibilities were identified for the Radiation oncologist, eleven for the Medical physicist, five for the Medical dosimetrist, two for the Radiation oncology nurse, five for the Radiographer, three for the Anaesthetist, and six for the Operating theatre technician. However, the selected “core” team only included the team members, which were directly involved with seed implantation at the “Treatment delivery” stage of the LDR prostate brachytherapy while the patient is anaesthetised, e.g. Radiation oncologists, the Medical physics team, and the Radiation oncology nurse. Less focus was put on team members who helped with “maintaining” the patient, e.g. Anaesthetists, despite them using advanced equipment, such as heart rate monitors, blood pressure monitors, air flow monitors, etc., Operating theatre technician(s) who sometimes helped with the transport of the patient into the operating theatre, with moving the patient (e.g. manual handling) before the treatment, and cleaning the theatre after the treatment, etc.

3.5.4 Technologies

Both, “loose seeds” and “stranded seeds” LDR prostate brachytherapy treatments had a similar setup. They both used the TRUS probe for visual feedback, connected to the ultrasound, printer, stepper, template grid, needles, and a computer with advanced software for 2D and 3D modelling (e.g. VariSeed). However, the difference between the two techniques was in the use of the Mick® applicator, and the radioactive seed format. “Loose seeds” came prepacked in a shielded container and were stored in a stainless steel cartridge. The cartridges were inserted in the Mick® applicator one by one, and the radioactive seeds were then individually implanted into the patient’s prostate gland through the pre-planted needles. “Stranded seeds” also came prepacked in a shielded container, but had to be manually cut based on the treatment plan, and then inserted directly into the prostate gland through the pre-planted needles. Because the radioactive seeds were not shielded any more once they were removed from the container, the team had to wear lead body aprons as part of the personal protective equipment. The lead body aprons were taken off after the radioactive seeds were all implanted, at the end of the LDR brachytherapy treatment. In both techniques the radioactive seeds stay permanently implanted in the patient’s prostate gland. The characteristics of both, “loose seeds” and “stranded seeds” LDR prostate brachytherapy are described in more detail in section 2.2.10 of this thesis.

3.5.5 Hierarchical Task Analysis

Hierarchical Task Analysis (HTA) was developed for every team member’s operation and sub-operation at the “Treatment delivery” stage of the LDR prostate brachytherapy cancer treatment during the observational period of thirty two treatment cases. After identifying the main operations, they were developed further into a number of sub-operations. All together 41 “main” operations and 223 subsequent operations were recorded by using the HTA for:

- “Loose seeds” technique: performed in three hospital sites (sites 1-3)
- “Stranded seeds” technique: performed in one hospital site (site 4)

In "loose seeds" brachytherapy, 8 operations and 47 sub-operations were recorded for the Radiation oncologist, 7 operations and 29 sub-operations for the Medical physicist #1, 3 operations and 16 sub-operations for the Medical physicist #2, 2 operations and 18 sub-operations for the Nurse, and 2 operations and 16 sub-operations for the Anaesthetist. The 8th operation with 8 sub-operations for the Radiation oncologist were only performed on one hospital site as it was an experimental operation, and not crucial for the LDR brachytherapy treatment. In other hospital sites the Radiation oncologist only performed seven operations and consequently 38 sub-operations.

In "stranded seeds" brachytherapy, 4 operations and 21 sub-operations were recorded for the Radiation oncologist, 4 operations and 15 sub-operations for the Radiologist, 6 operations and 16 sub-operations for the Medical physicist #1, 2 operations and 11 sub-operations for the Medical physicist #2, 2 operations and 14 sub-operations for the Nurse, and 2 operations and 20 sub-operations for the Anaesthetist.

HTA was previously successfully applied to the healthcare in the past. For example Lane, Stanton et al. applied HTA to medication administration errors (2006), surgical training (Arnold and Farrell 2002), laparoscopic surgery (Joice, Hanna et al. 1998), complex anaesthetists' tasks associated with the ultrasound-guided axillary brachial plexus blockade (O'Sullivan, Aboulafia et al. 2011), assessing nurses' mental workload in High Dosage Radiation treatment room (Mosaly, Xu et al. 2010), amongst others. HTA has been mentioned as one of the most commonly used 'human reliability' techniques in healthcare (Lyons, Adams et al. 2004).

The objective of using the HTA in this project was to draft enough sub-operational steps to fit the operations to the level where they still had a meaning, without going into too much detail. Splitting sub-operations further would be too cumbersome. All operations and sub-operations were validated by the team members. The main operations identified in the Hierarchical Task Analysis were used for collecting data on perceived workload across four hospitals in Ireland. More details on the perceived workload is in the next chapter of this thesis.

The HTA data in the Results section is presented in tabular format to fit the thesis format. No HTA diagrams were drawn due to space restrictions in this thesis. For example, Figure 3-2 shows an example of the “left-right” HTA diagram for some of the Medical physicist’s operations and sub-operations at “loose seeds” LDR brachytherapy, and it is already taking a considerable amount of space.

Hierarchical Task Analysis for operations performed by the Radiation oncologist and the Radiologist at site 4

The operations for the Radiation oncologist and the Radiologist were mapped together, and were performed one after another. Their timeline of operations performed is presented in Figure 3-5. The first operation was performed by the Radiation oncologist. The second and third operations were performed by Radiologist. Fourth operation was then again performed by Radiation oncologist. Fifth Radiation oncologist’s operation was performed in front of the patient following the feedback on the ultrasound display. Sixth Radiologist’s operation was performed straight after the fifth Radiation oncologist’s operation, and required following the “seed placement” on the computer and ultrasound display. The same “Seed placement” word was used for both operations despite different sequence of sub-operations. The seventh operation was then performed simultaneously between both of them, which is why they were both numbered as “seventh”.

3.5.6 Research limitations to mapping the LDR prostate brachytherapy

The research limitations related to during mapping the LDR prostate brachytherapy treatment included:

- Prohibition of using audio or video materials as part of the ethical clearance. This excluded producing any type of photographic or video material during the LDR prostate brachytherapy treatment. Though taking audio or video may help with a more detailed understanding of user-system interaction on a time-motion basis, and with even more detailed HTA.
- Only a single observer was used during the observational period, using pen &

paper technique. Observational data was validated with informal discussions with the core team members after the treatment cases.

- The observation was done during the LDR prostate brachytherapy treatment process in the real clinical environment, strictly without interrupting or interference of the core team members.
- Space limitation: Some HTA sub-operations could be developed even further, but were left as they were, because they contained enough information for this research. If continued, some sub-operations could become too detailed and too long. Nevertheless, all sub-operations were included, and none of them were left out of the research context.
- Site limitations: The mapping of “Treatment delivery” stage of LDR prostate brachytherapy treatment process was performed only across four hospital sites in Ireland. Three of these sites with the “loose seeds” LDR brachytherapy technique used the same sequence of operations and sub-operations. The exception was on one site, which had an additional eighth operation and sub-operations, which was clearly noted in HTA. Only one site with the “stranded seeds” LDR brachytherapy technique was used to map the operations and sub-operations. The HTA results may have been different if more sites which apply either LDR prostate brachytherapy treatment modality participated in the research.

3.5.7 Future work and recommendations to mapping the LDR prostate brachytherapy

Future work and recommendations to mapping LDR prostate brachytherapy may include analysis and techniques, which are beyond the scope of the research presented in this thesis:

- The use of audio and video materials for a more detailed and specific analysis, e.g. ‘time-and-motion’ studies, ‘teamwork’ studies, ‘human error’ studies, etc. This, however, should need to be well defined, described, and covered in the Ethics Committee application.
- A group of observers rather than a single observer: despite space limitations,

more than a single observer could provide a more in-depth clinical observation, focussing on specific team members, their physical movements, verbal communication patterns, user-user, user-system interaction, etc.

- Mapping the “Treatment delivery” stage of LDR prostate brachytherapy treatment process at other hospital sites elsewhere in Ireland, and abroad: despite the AAPM guidelines, there may be some technology-specific main operations and sub-operations deviations.
- Applying other ‘cognitive’, ‘human error’ and ‘human reliability’ methods, such as FMEA, RCA, HAZOP (Dhillon 2003) etc., and combining them with Quality Assurance principles, such lean, six sigma (Hignett, Jones et al. 2015) etc., safety climate, safety culture (Pronovost and Sexton 2005), etc., along with the departmental staffing changes and technological advancement.

3.6 Conclusions

Hierarchical Task Analysis was developed during the observational period of thirty two treatment cases. HTA was developed for each core team member at “stranded seeds” and “loose seeds” LDR prostate brachytherapy. The main focus was on the following core team members: Radiation oncologist, Medical physics team, Radiation oncology nurse, and Anaesthetist. Their interaction with the technologies, as well as individual person-to-person interactions was mapped, along with a detailed HTA. Mapping the LDR prostate brachytherapy process gave a deeper, more detailed understanding of individual roles in a team, team member responsibilities during the treatment, how the technologies are used during the treatment process, and the differences in team members and technologies used between two LDR prostate brachytherapy treatment modalities. Mapping the treatment process, especially identifying the “main” operations of each core team member, served as a basis for the further research on the topics of perceived workload and automation, presented in later chapters of this thesis.

3.7 Chapter summary

This chapter introduced a mapping approach to ‘Low-Dose Rate’ brachytherapy “Treatment delivery” process. After initial literature review and general familiarisation with the treatment process, observational period identified and presented the User-System interaction between core team members and the technologies, and developed, validated and presented the Hierarchical Task Analysis for “loose seeds” and “stranded seeds” LDR prostate brachytherapy treatment. The main operations identified in Hierarchical Task Analysis are later on used in assessing the perceived workload and ‘levels of automation’, which are the topics of the next few chapters.

Chapter 4: Workload

4.1 Chapter overview

This chapter introduces one of the core topics of this research: perceived workload. The introduction explains workload terms, terminology, why the workload is important, it presents workload facts, issues and challenges, it provides examples of physiological and subjective workload, it gives an overview of “ISO EN 10075 - Ergonomic principles related to mental workload” standard, and it presents research examples of perceived mental workload measurements in radiotherapy and brachytherapy. The method section introduces the NASA-TLX method, which was used in this research, it provides an example of how to calculate the overall workload score and the proportion of the TLX dimensions based on the NASA-TLX worksheet, and explains the objectives of applying NASA-TLX in this project. Besides the overall workload scores and the proportion of the TLX dimensions obtained with the NASA-TLX, new tools were developed and applied, such as the “Workload rating scale” and the “Revised workload rating scale”, which helped identifying the critical workload levels of perceived workload. The results section presents the overall workload scores and the proportion of TLX dimensions for each core team member’s operation (or a “task”) across four hospital sites, identifies critical levels of perceived workload, and the operations where these critical levels of perceived workload occurred. The discussion provides besides discussing the results, also the challenges of applying NASA-TLX method to the clinical environment, the “Workload rating scale”, critical workload levels, and red-line criteria. The conclusions present the crucial workload findings and their relation to the topic introduced in the next chapter: automation and ‘levels of automation’ in LDR prostate seed brachytherapy.

4.2 Introduction

4.2.1 The terms

In Merriam-Webster online dictionary (Merriam-Webster.com 2013), *workload* is defined as:

"1. The amount of work or of working time expected or assigned.
2. The amount of work performed or capable of being performed (as by a mechanical device) usually within a specific period."

"Mental workload" involves "mental and physical activities" in man-machine system and is defined as "the operator's evaluation of the attentional load margin (between their motivated capacity and the current task demands) while achieving adequate task performance in a mission-relevant context" (Jex 1988).

"Mental workload" is a multidimensional concept, and Dudek and Koniarek (1995) report that "*there is no one method that would be the best to assess the level of the employee at the workplace*". It is determined by the characteristics of the task (e.g. demands, performance) and of the operator (Leplat 1978; Stanton, Hedge et al. 2004). Similarly, workload is also described as "the proportion of capacity that is used to perform a task" (de Waard and Lewis-Evans 2014). In general, the term "mental workload" comprises of two components: stress (task demand) and strain (the resulting impact upon the individual) (Stanton, Hedge et al. 2004). Furthermore, the term "mental workload of a task" is defined as "the level of attentional resources required to meet both objective and subjective performance criteria, which may be mediated by task demands, external support and past experience" (Young and Stanton 2001). However, the term "workload" is more "human-centred" than "task-centred" and is described by Hart and Staveland (1988) as the "*operator's subjective experience summarised by the influence of many factors in addition to the objective demands imposed by their task. It emerges from the interaction between the requirements of a task, the circumstances under which it is performed and the skills, behaviours and perceptions of the operator*". Workload is a metric for quality and safety (Mazur, Mosaly et al. 2014) and for optimal performance to provide a safe working environment (Nachreiner 2003). It is also reported that the performance is the highest at moderate levels of workload (Nof 2009; Bruggen 2015).

Moreover, International Organisation for Standardisation (ISO) standard 10075 defines the term "mental stress" as "any external influence pinging upon human beings and affecting them mentally" and that "any activity – even a physical one – can impose mental stress" (ISO 1991).

4.2.2 Workload terminology

Although Jex (1988), Young and Stanton (2001), and Stanton et al. (2004) used the term “mental workload”, this term should be exercised with caution, because it often involves both, mental and physical activities. NASA-TLX authors Hart and Staveland (1988) who developed it refer to this term simply as “workload”, and not “mental workload”. Therefore, in this thesis workload will be referred to as “perceived workload”.

4.2.3 Why is workload important?

Humans have a limited working capability when it comes to processing information, performance, memory, coping with the tasks, ability to manage a range of tasks, etc. Excess load can lead to errors, slips, mistakes and can influence performance (Wilson and Russell 2003). Too much workload can make people tired, stressed, it can increase the risk of sickness; they may perform tasks rushed; they may be unable to make decisions at the given time due to task overload, complexity and number of decisions, etc. Too little workload can make people mentally unchallenged, bored, fatigued, un-alert, careless, distracted, negligent and ineffective, and can lead to monotony and task errors; it can also result in poor job satisfaction. These factors have been referred to as “issues during interactive human/machine” tasks (Jex 1988) and “issues in Human-Centred Automation” (Wise, Hopkin et al. 2009). The workload levels when the assessed workload is “too high” or “too low” can play a crucial role in patient safety and can compromise not only patient safety, but also the safety of the medical teams during the treatments or surgical procedures.

HSE (UK) reports that workload is related to competence, working hours and working patterns, organisational change and staffing levels (HSE n.d.). A high workload can affect safety and has a negative effect on job satisfaction, which corresponds to staff turnover and staff shortage (HSE n.d.). Furthermore, job stress, low staffing levels and “high physical workload” are reported as one of the factors of increased workload among radiotherapy professionals (Carayon P. 2008; The Royal

College of Radiologists, Society and College of Radiographers et al. 2008; Sehlen, Vordermark et al. 2009; Hutton, Beardmore et al. 2014; Lievens, Defourny et al. 2014). Interestingly, workload was reported as one of the contributing factors in the job satisfaction survey among radiotherapy professionals in the UK. One of the common factors contributing to increased workload was introduction of the "new technology" (Hutton, Beardmore et al. 2014). Besides new technology, two negative effects that were reported as negative to increased workload were machine reliability and downtime (Hutton, Beardmore et al. 2014). Understanding and assessing workload in radiotherapy represents one of the approaches in addressing the safety issues within radiotherapy, and more particular, within LDR prostate brachytherapy. This is one of the reasons why the focus of this thesis is on identifying critical workload levels among healthcare professionals and on human-automation interaction before relating it to other factors, before it is combined with the research on the occurrence of incidents and errors, and other factors which directly or indirectly contribute to patient safety.

4.2.4 Workload facts, issues and challenges

Workload can be measured at a certain point in time, and can also change over time, when new technologies, new working patterns or new staff members are introduced. When measuring workload in a team, it is important to assess the whole team (that is, the individuals in a team), not just the selected individuals, as different team members can influence each other via shared tasks, visual and verbal communication, etc. It is also important that staff members know their role (especially of their Standard Operating Procedures, or "SOPs") in order to achieve optimal and consistent performance. There may be different responses to the same tasks by experienced and inexperienced operators. Workload may also vary due to their past and future work obligations. For example, workers can come to work stressed or tired due to the previous work they did, they can rush the tasks if they do not have much time available, if they have to be somewhere else straight after their working session, etc. Common issues with workload are as well that when physical workload decreases, mental workload increases (Wickens and Huey 1993; Wise, Hopkin et al. 2009).

In addition, certain professions are designed to involve low or high mental workload. For example, professions with higher mental workload are Air Traffic Controllers, Pilots, Military Commanders, Nuclear plant operators, Surgeons, etc. These professions generally require a lot of previous training and experience. Professions with lower mental workload are Assembly line technicians, Maintenance operators, Cleaners, etc. Workload can also decrease with time (Jex 1988). It can also be different from person to person due to their own psycho-physiological endowments, different training, recent practice, etc (Jex 1988). It also does not always have to be high or low either, it can fluctuate between the two. Sometimes it can be high for a certain period of time, or it can be low, medium, etc. Workload fluctuation fits most human beings, because they can cope with this and recuperate more easily than with "steady" workload, which requires high focus and concentration over a certain time period. For example, even Air Traffic Controllers who need to be highly focussed, work for a maximum of one hour, followed by half an hour off before their next hour, in an eight-hour shift due to such a high workload (Benedictus 2008).

Some tasks performed with using a machine or computer (software) utilise human input. Tasks are harder if a person is unexperienced with the machine or computer, if there are technical problems that need to be fixed, etc. Fixing problems can add additional time to get the machine or computer back into working order. However, some tasks can be done very easily and ease human workload, if they are designed correctly, and if the person has received sufficient training. For more details refer to the "Human-Automation" section in this thesis.

Assessing workload can improve performance and identify the factors, tasks or sub-tasks (or more correctly, "operations" and "sub-operations") that need further improvement. As mentioned above, it is at the given time and space the workload can be measured. These measurements can serve as a benchmark for the immediate improvements of the existing working environment. They can serve as a benchmark for future performance measurements in case of work environment changes, e.g. if there are staff changes, when new software or hardware is introduced, etc. They can also serve as a benchmark for optimal performance, e.g. increased workload may result in decreased performance (Mazur, Mosaly et al. 2014).

4.2.5 Workload measurement

a) Physiological workload

Physiological workload is usually considered as physiological measurement of a person's activity in performing the task(s) and/or subtask(s). They often require continuous monitoring of data over a given time and expensive (specialist) equipment. Physiological workload measurement is also known as "objective" workload measurement (Jex 1988). Physical capabilities involve the measurement of the cardiovascular system (e.g. heart rate, blood pressure, blood flow), respiratory system (e.g. respiration rate, oxygen consumption, etc.), nervous system (e.g. EEG for brain activity), eye functions (e.g. eye movement, blink rate, pupil response, pupil size, pupil gaze, etc. (Stanton, Hedge et al. 2004; Wilson and Corlett 2005; Wise, Hopkin et al. 2009).

b) Subjective workload

Subjective workload is usually less expensive than physiological workload, and is typically measured subjectively straight after the person's activity in performing the task(s) and/or subtask(s). The ratings depend on the individual's perception of the workload of their tasks and subtasks at a given point in time. As written by Bruneau, the subjective workload assessment is "*asking the person themselves to estimate the amount of load placed on his or her cognitive system for performing a certain task*" (Karwowski 2007). The methods include questionnaires, structured interviews, verbal, written or computer-based rating scales and techniques. The methods can be one-dimensional (they provide a single scale with a general workload score) or multi-dimensional (they are more complex and can provide some workload diagnostics) (Stanton, Hedge et al. 2004; Wilson and Corlett 2005). A number of Human Factors workload methods exist, e.g. Cooper & Harper Scale (Cooper and Harper Jr 1969), Subjective Workload Assessment Technique (SWAT) (Reid, Eggemeier et al. 1982), NASA-TLX (Hart and Staveland 1988), Subjective Workload Dominance (SWORD) technique (Vidullch, Ward et al. 1991), Thurstonian scaling (Dudek and Koniarek 1995), Simplified SWAT (Luximon and

Goonetilleke 2001), etc. They have been successfully applied to a number of different industries, e.g. aviation, nuclear industry, software evaluation, automotive industry, etc. (Hart 2006). Some subjective rating scales include additional tasks to be performed at the time of assessment, such as sorting cards which involves decision making (e.g. SWAT), etc. These additional tasks may be more easily applicable in the simulated environment and less applicable in the real working environment, e.g. pilot flying an airplane, train driver operating the train, or a surgeon performing an operation in the operating theatre.

4.2.6 ISO EN 10075: Ergonomic principles related to mental workload

The International Organisation for Standardisation (ISO) developed a standard that deals with workload already in 1991 (ISO 1991). Since then, a number of related standards have been developed and updated:

- ISO 10075:1991 - Ergonomic principles related to mental workload - General terms and definitions
- ISO/NP 10075-1:1991 - Ergonomic principles related to mental workload - Part 1: General concepts, terms and definitions
- ISO 10075-2:1996- Ergonomic principles related to mental workload - Part 2: Design principles
- ISO 10075-3:2004 - Ergonomic principles related to mental workload - Part 3: Principles and requirements concerning methods for measuring and assessing mental workload

These standards have been implemented internationally in the UK, Germany, Japan, etc. They emphasise the reasons why mental workload is important, provide terminology in this field, general concepts of mental workload, work design guidelines, requirements for assessment methods, etc. They also emphasise that the standard does not assess only physical activity, but the overall work activity (Nachreiner 1995). Workload assessment is an assessment of the “objective” features of the working conditions, and that such an assessment is set to optimise, not minimise mental stress and to provide a safe working environment (Nachreiner

2003).

4.2.7 Workload assessments in Radiotherapy and Brachytherapy

The objective and subjective workload assessments were researched in different scenarios by (Young, Zavelina et al. 2008; Mosaly, Xu et al. 2010; Mosaly, Mazur et al. 2011; Mazur, Mosaly et al. 2012; Mazur, Mosaly et al. 2013; Galičič M. 2014; Mazur, Mosaly et al. 2014). All of these workload assessments were using the NASA-TLX method. More about the NASA-TLX method is written in the Methods section.

In one research study Mosaly et al. (2011) were evaluating workload of the Medical physicist during the EBRT "Planning and delivery" stage in order to identify tasks that might compromise patient safety. Medical physicists play an important role in the radiation oncology system. High workload may result in sub-optimal performance leading to errors. Seven participants were observed over 10 days in a clinical environment. The workload was assessed at 6 stages by using NASA-TLX worksheets. A high workload of 55 or higher was reported in all tasks, especially after the "Treatment planning" and "Quality checks" tasks. The dimensions with the highest scores were "Mental demand", "Effort" and "Temporal demand". Furthermore, no significant differences were observed between the tasks. The main contributors to the high workload were software malfunctions and missing information or notes, which resulted in rework. The authors proposed that the solutions were improved communication, standardised workflow, and simplified and mistake-proofed working environment (Mosaly, Mazur et al. 2011).

Quantitative assessment of workload stressors in clinical radiation oncology were researched by Mazur et al. (2012). They reported that these can lead to sources of errors. The workload of 21 study participants, including Simulation therapists, Radiation therapists, Radiation oncologists, Dosimetrists and Medical physicists were assessed in a real working environment during the EBRT "Planning and delivery" stage by using the NASA-TLX method. 173 TLX assessments were obtained, ranging from low (30-36; among Simulation therapists), medium (40-52;

among Radiation oncologists, Radiation therapists and Dosimetrists) to high (51-63; among Medical physicists) workloads. Stressors were assessed based on the observational data collected during the research. They were technical (software or hardware) stressors, environmental stressors (based on work conditions), and teamwork stressors (e.g. information exchange). 5 stressors per case were observed for Simulation therapists, Radiation therapists and Dosimetrists, while 3 stressors per case were found for Medical physicists and Radiation oncologists. Furthermore, the authors stated that the evaluation of workload could be considered one of the independent measures to assess the Quality Assurance of the processes used to deliver Radiotherapy to patients and to contribute to redesign or development of future environments and technologies to support safe patient care (Mazur, Mosaly et al. 2012).

The relationship between the workload and performance among nine Radiation oncologists during radiotherapy planning stage was studied by Mazur et al. (2013). They related workload levels to performance decline. In a simulated environment, they were measuring pupil size and blink rate together with a subjective measurement tool called NASA-TLX on three tasks in two cases. The overall data was collected on 18 cases and 54 tasks. They concluded that performance started to decline at ≥ 55 and that NASA-TLX is “*a reasonable method to quantify subjective workload for broad activities*” (Mazur, Mosaly et al. 2013).

In another research study, Mazur et al. (2014) related workload with errors during EBRT “Planning” stage. They used direct and video observations to detect, evaluate and to rate errors based on the severity grade. In a simulated environment, nine Radiation oncologists were assessed on 3 cases. Overall, 18 out of 27 cases had no noted errors. They discovered that workload levels reached potentially “unsafe levels”, that is, TLX levels above 50. Performance also declined at TLX score above 50. They also concluded that workload is to be “*considered as a metric for quality and safety as suboptimal workload levels appear to be related with reduced performance*”. Also, “Mental demand” was a major source of the overall TLX variation (Mazur, Mosaly et al. 2014).

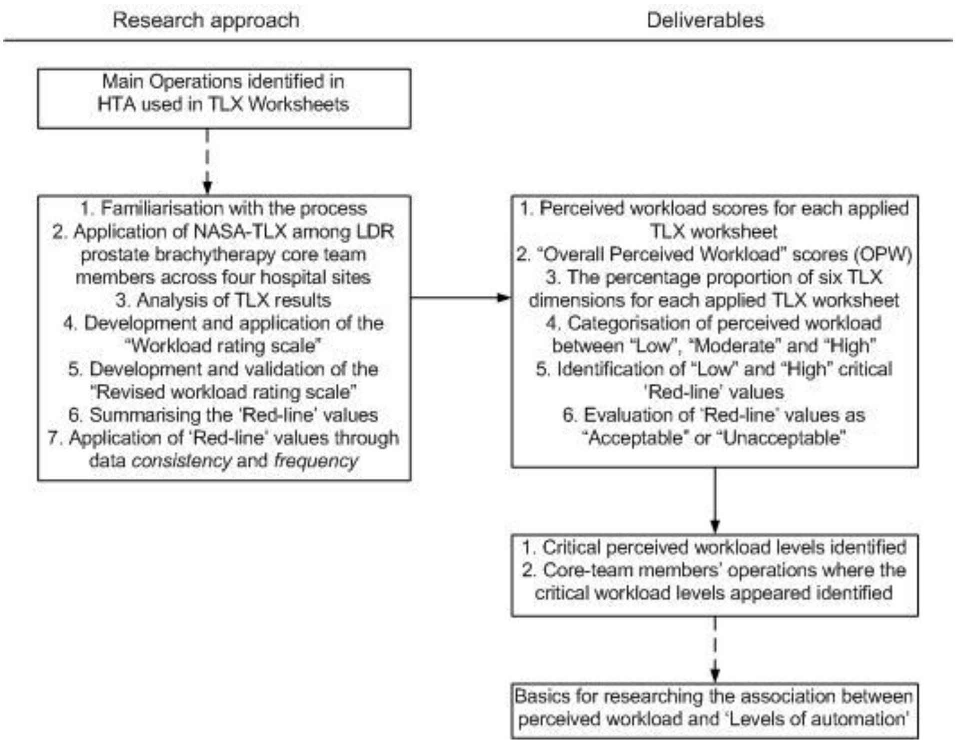
Mental Workload of Medical Physicists, Radiation Therapists and Dosimetrists at the five stages of Radiation treatment planning in EBRT using NASA-TLX was assessed by Galičič (2014). The authors administered 105 TLX worksheets in 21 cases at each of the 5 stages of Radiation treatment planning in the clinical environment. Furthermore, they also identified errors that occurred during the observation via two error-reporting systems: Physics check and Therapist check. All five stages reported medium to high workload levels. High workload scores were reported in five out of seven cases with reported errors. Only one out of seven errors had high severity score. This error originated in the previous stage, and was discovered and eliminated at the treatment planning stage. The highest contributing workload dimensions were "Temporal demand", "Effort" and "Frustration" (Galičič M. 2014).

Workload assessment in HDR brachytherapy on nursing staff was performed by Mosaly et al. (2010). Their objective was to perform a detailed Task Analysis and to assess workload in order to identify the most critical tasks for further evaluation. They concluded that the nurse performs 14 separate tasks, which require high levels of cognitive and physical capabilities under high time pressure. The examples of high workload listed were distress, burnout, job dissatisfaction, absenteeism, high turnover and poor job performance. Six treatment procedures were observed, and workload data was collected. A "Systematic Human Error Rate Prediction Approach" (SHERPA) technique was applied to Task Analysis tasks and sub-tasks to identify potential errors related to human activity. Four tasks were identified to have high TLX scores of above 55. TLX results ranged from 33.3 to 60.6. SHERPA method identified 14 errors with higher-medium potential of occurrence and low-high criticality of errors, which may lead to accidents. They concluded that it was "*important to evaluate staff workload to predict potential errors*" (Mosaly, Xu et al. 2010).

4.3 Methods

This section introduces the characteristics of the NASA-TLX as a method for assessing the perceived workload, how it should be applied, and how to calculate the workload data from the TLX worksheet. Furthermore, it presents the methodical approach from collecting and analysing the data, categorising the TLX workload scores, applying 'Red-line values' for specific core team member's operations, and identifying if these values could compromise patient safety. The research approach, along with the deliverables is summarised in Figure 2-1. The deliverables are discussed in more detail in the next few sections of this chapter.

Figure 4-1 Methodical approach to assessing perceived workload by using NASA-TLX method, and steps to identifying potential safety critical operations



4.3.1 Perceived workload and NASA-TLX

National Aeronautic Space Administration (NASA) Task Load Index (TLX) is a self-reported subjective technique for assessing mental workload measurement tool that was developed by NASA in 1998 (Hart and Staveland 1988). The workload is assessed at six dimensions:

- Mental Demand (MD)
- Physical Demand (PD)
- Temporal Demand (TD)
- Performance (PE)
- Effort (EF)
- Frustration (FR)

The technique can be computer based or paper based, and uses the same principle described by Hart and Staveland (1988). Paper based technique consists of a specifically designed worksheet, often referred to as the “TLX worksheet”, or just the “worksheet”. It is a single page on a sheet of paper administered to the user. The worksheet consists of two parts:

1. Six scales (one for each dimension) where the perception of each dimension is measured on a scale between 0 and 100
2. Fifteen pair-wise comparison tiles, where each dimension is matched on a one-to-one basis with every other dimension, e.g. EF vs. PE, TD vs. FR, TD vs. EF, etc.

Each scale has two endpoints (low/high or good/poor) and is defined individually as per Hart and Staveland (1988). The endpoints and the definitions are presented in Table 4-1. An example of the TLX worksheet can be found in the Appendix A. The computer based technique follows the same technique as the paper-based technique, and was adopted to digital format, e.g. computers, tablets, etc. For the purpose of this research, a paper-based technique was applied at the “main” operations to individual core team members in LDR prostate brachytherapy treatment.

Table 4-1 NASA-TLX dimensions, endpoints and definitions

Workload dimension	Endpoints	Definition
Mental Demand	Low / High	How mentally demanding was the task?
Physical Demand	Low / High	How physically demanding was the task?
Temporal Demand	Low / High	How hurried or rushed was the pace of the task?
Performance	Low / High	How successful were you in accomplishing what you were asked to do?
Effort	Good / Poor	How hard did you have to work to accomplish your level of performance?
Frustration	Low / High	How insecure, discouraged, irritated, stressed and annoyed were you?

4.3.2 Calculating the overall workload score and dimensions contribution

To calculate an overall workload score it is best to use a table format presented in Table 4-2 (Hart and Staveland 1988):

1. Start with an empty table indicating all the necessary factors for the analysis.
2. In the “Weight” column write down how often each dimension appears in each pair-wise comparison tile; the sum of all tiles should be 15, one per each tile; it is OK to insert zero in there.
3. In the “Raw rating” column write down the rate from a scale from each dimension; twenty one thick marks on each scale divide the scale from 0 to 100 in increments of 5, therefore the value for analysis is a number between 0 and 100; Hart and Staveland (1988) suggest that if the value is in-between the increments, the closest value to the right should be written down and rounded to the increment of 5. However, in this research, the values in-between the increments were not rounded up in order to create a more precise set of results.
4. In the “Product” column, write down a multiplied score of “Weight” and “Raw rating” for each dimension, multiplied horizontally.
5. In the “Product sum” bracket, write down a sum of “Product” scores, summed up vertically.
6. In the “overall workload score” bracket, divide the sum of products by 15; the number 15 is selected to match the number of pair-wise comparison tiles.
7. In the “Dimensions” column write down the proportion of each dimension (in percentage); the proportion of each dimension is calculated based on the individual sum of each product and the product sum; the dimensions proportions should never be over 100; the dimensions can also be presented graphically (Hart and Staveland 1988). Note that each TLX worksheet gives a proportion of six TLX dimensions: MD, PD, TD, PE, EF and FR.

An example of obtaining an overall workload score and dimensions proportions from the TLX worksheet is presented in Table 4-2.

Table 4-2 An example of obtaining an overall workload score and dimensions proportions by using NASA-TLX method

Dimension	**Weight**	**Raw rating**	**Product**	**Dimension (in %)**
MD	5	65	325	33
PD	0	35	0	0
TD	2	40	80	8
PE	4	75	300	30.5
EF	3	75	225	23
FR	1	55	55	5.5
Weight sum	15	**Product sum**	**985**	
		Overall workload score (Product sum divided by 15)	**66**	

4.3.3 Application of NASA-TLX in this project

Paper-based TLX worksheets were applied to assess workload among the LDR prostate brachytherapy core team members in four different hospitals in Ireland. Hospitals used either “loose seeds” LDR brachytherapy technique, or a “stranded seeds” LDR brachytherapy technique. The principles of each LDR prostate brachytherapy technique are described in previous chapters. Each core team member had to fill out a TLX worksheet prepared specifically for their role and matched with their “main” operations previously identified and developed with Hierarchical Task Analysis: Radiation oncologist, Radiologist, Medical physics team (referred to as “Medical physicist #1” and “Medical physicist #2”), Radiation oncology nurse, and Anaesthetist. The TLX worksheets were filled out immediately after they were administered to each individual team member straight after the LDR prostate brachytherapy treatment case. Sometimes the worksheets were filled out at a later stage due to busy schedules, e.g. meetings, other treatments, seeing other patients, etc. This presented additional challenges of data collection which were discussed in detail by the author (Galičič, Fallon et al. 2013). However, the preferred way was for the individuals to fill out their TLX worksheets immediately after the treatment. Besides collecting data on perceived workload, it was also possible to be present and to observe LDR brachytherapy treatment cases in addition to the observational period, used for development of the Hierarchical Task Analysis. These observations focussed more on observations of perceived workload, and how could, potentially, main operations of the core team members, be interfered, or even compromised by either user-system interaction or user-user interaction (communication patterns between the core team members). This is discussed in more detail in the Results and Discussion sections of this chapter.

A detailed description of the main operations of each core team member per site is presented in Section 3.4.4. TLX worksheets were administered to the main core team members' operations at both, "loose seeds" and "stranded seeds" LDR prostate brachytherapy. The main operations for "Loose seeds" LDR prostate brachytherapy are presented in Table 3-5, Table 3-6, Table 3-7, Table 3-8 and Table 3-9. The main operations for "Stranded seeds" LDR prostate brachytherapy are presented in Table 3-10, Table 3-11, Table 3-12, Table 3-13, Table 3-14 and Table 3-15. An additional "Overall Perceived Workload" (OPW) TLX worksheet was administered in addition to the "main" operations to Radiation oncologists and radiologists to benchmark the applicability of the TLX worksheets. OPW assessed the workload of all operations together on one TLX worksheet, in comparison to individually administered TLX worksheets. Details on comparison on the OPW TLX worksheets against the individually administered TLX worksheets are in the Results and Discussion sections of this chapter.

4.3.4 Workload rating scale

The 'Workload rating scale' (2013) presented in Table 4-3 was applied to the overall workload scores obtained with the TLX worksheets. The cut-off point for high workload was selected as 55 or greater, taking into account the workload score variability and following from the work of Mazur et al. (2012) and Mazur et al. (2013). Previous work by Knapp and Hall (1990) considered high workload at ≥ 40, while Lee et al. (2001) considered high workload at ≥ 50. However, the cut-off point of 55 or greater corresponds with the research by Mazur et al. (2013) who reported that performance declines at this score.

Table 4-3 The ‘Workload rating scale’

Workload level	Workload score level
Low	< 35
Moderate	35 - 55
High	> 55

4.3.5 Critical levels of perceived workload

After the above workload rating scale was applied to the results, the question regarding the critical levels of perceived workload remained the same: what are the critical workload levels that could compromise patient safety, how can they be identified, and at which core team member’s operations do the critical perceived workload levels appear? These two questions were also the first two research questions in this thesis.

As mentioned before, workload can fluctuate between low, moderate and high. The above workload rating scale clearly identified these levels of workload. However, it did not identify the “critical levels” of perceived workload. Critical levels of workload can be explained as the workload levels where the workload is on one hand “too high”, and on the other hand “too low”. The issue of “too high” workload has also been highlighted by (Hart 2006). However, Hart (2006) provided no solutions for this issue. In terms of human performance, if workload is “too high” or “too low” it means the level of workload is unacceptable for the working environment and further analysis, and possibly, a job redesign, or detailed evaluation is required to alleviate this condition. The term “red-line” is often referred to as a level when the workload is “too high”. This term has been researched mostly in relation to SWAT analysis (Reid and Colle 1988; Colle and Reid 2005). However, the red-line does not mean that “high” workload levels are unacceptable. For higher workload the red-line indicates the level at which the workload starts accelerating, and special attention should be paid to the consistency and frequency of such reported values (Reid and Colle 1988). Such values are accepted for a while, but can be problematic after a certain time (Reid and Colle 1988), because they can lead to decreased performance, worker’s overload and consequently increased levels of workload, and potentially to the increased errors which can in healthcare compromise patient and/or operator’s safety. In other words, the red-line is an indicator of critical levels of perceived workload.

4.3.6 The ‘Revised workload rating scale’

The above ‘Workload rating scale’, developed and successfully applied to individuals in LDR prostate brachytherapy team (Galičič, Fallon et al. 2013) was revised to determine the red-line levels of the NASA-TLX method. The following characteristics were researched:

- The workload is “too low” when it is rated as zero, or close to zero
- The workload is “too high” when it reaches the already established level of “high” workload rated as 55 or above
- Scale increments and red-line: the breadth of the increments which categorise low, moderate and high workload is similar as the previous workload rating scale to match the scale proportions. Therefore, the increments for “low” workload have been changed to 0 and 30 on the NASA-TLX scale. The red-line for “too low” workload is 5, and covers the values between 0 and 5. The increments for “high” workload are between 50 and 55 on the NASA-TLX scale. The red-line for “too high” workload is 50, and covers the values between 50 and at 55. Values of 55 and over are still determined as “too high”, and are therefore “unacceptable”.

The ‘Revised workload rating scale’ incorporates the red-line for when workload is “too low” at 5, and when it is “too high” at 50 on the NASA-TLX scale. The red-line score levels are presented with bold red colour in Table 4-4. As mentioned above, any values marked with * in Table 4-4 should at least look into *consistency* and *frequency* of the reported values. If at least one of these two factors is present, then the “acceptable” values should be changed into “unacceptable”. The red-line values can act as an indicator of critical levels of perceived workload.

Table 4-4 The 'Revised workload rating scale'

Workload level	**Workload score level**	**Criticality**
Too low	0 - **5**	Acceptable, or *unacceptable* *
Low	**5** - 30	Acceptable
Moderate	30 - **50**	Acceptable
High	**50** – 55	Acceptable *
Too high	> 55	*Not acceptable*

* *Red-line values*

To conclude this section, it is proposed that the following steps are taken for tackling the workload critical levels with the 'Revised workload rating scale':

1) Apply the 'Revised workload rating scale' to the workload scores (decide if mean or median values are used)
2) Categorise the workload scores between low, moderate and high
3) If any of the categorised workload scores "cross" the red-line either for when the workload is "too low" or "too high", check for *consistency* and *frequency* of the workload scores; use additional check-lists and analysis if necessary
4) Confirm the workload categories; if all are "acceptable", no further action is necessary; if some are "unacceptable", further investigation of operations may be needed.

4.4 Results

The results for perceived workload were obtained by the application of descriptive statistics, presenting two sets of data: one for the overall workload scores of perceived workload, and one for the dimension proportions of the overall workload scores. The data is presented per site and per each core team member separately. Furthermore, the overall workload results were then ranked between "low", "medium" and "high" workload after the application of the "Revised workload rating scale", after which the "Red-line" values were identified for when workload was "too low" or "too high".

4.4.1 Perceived workload

A summary of overall workload scores

Thirty two LDR brachytherapy treatment cases were observed before collecting data from 48 LDR brachytherapy treatment cases at four different hospitals in Ireland. Sites one and two were public hospitals, sites three and four were private hospitals. In total 1073 TLX worksheets were administered. 918 TLX worksheets were returned, giving the response rate of 85.6%; the response range was between 80.45% and 93.2%. A list of administered and returned TLX worksheets is presented in Table 4-5.

Table 4-5 A summary of administered and returned TLX worksheets

Site	Administered	Returned	Response rate (%)
1	242	203	83.8
2	391	333	85.1
3	220	177	80.45
4	220	205	93.2
Overall	1073	918	85.6

The overall workload scores and the percentage proportion of each contributed TLX dimension were calculated by using a pen and paper technique. They were calculated for each team member's operation in each hospital site by following the guidelines by Hart and Staveland (1988), as presented in the section 4.3.2 *Calculating the overall workload score and dimensions contribution*. The results of the paper * pen technique were at first calculated to two decimal numbers, and were rounded up to the nearest decimal with the SPSS program.

The overall workload scores

The overall workload scores were calculated for each core team member's operation per case per site. E.g. Radiation oncologist at Site 3 performed 7 operations over 10 LDR prostate brachytherapy cases, therefore 70 TLX worksheets were distributed in total (7x10), and out of 70 TLX-worksheets, 66 were valid. The complete data collected for each core team member per case per site is presented in Appendix C. Figures in this section present a summarised data collected for the overall workload scores per core team member per site with additional descriptive statistics, such as minimum and maximum values, mean, median, Standard Deviation, etc. Besides assessing the overall workload score, the worksheets for “Overall Perceived Workload” (OPW) were also administered along with the individual TLX worksheets to Radiation oncologists and Radiologists. The OPW worksheets were assessing operations 1-8 combined in one TLX worksheet to compare the OPW workload scores with the overall workload scores from individual operations. The OPW score was compared against the “Average median value” score of the assessed operations. The difference between the two average scores is presented in percentage in Table 4-6, Table 4-16, Table 4-26, Table 4-36, and Table 4-38.

TLX dimensions

The data on the proportion of TLX dimensions was assessed for each core team member’s operation per case for each site, along with the overall workload score. The complete data collected is also presented in Appendix C. Figures in this section present a summarised data collected for the TLX dimension proportion per core team member’s operation per site. Each TLX percentage proportion table includes an average TLX dimension proportion of the core team member assessed. In cases of Radiation oncologists and Radiologists, where the “Overall Perceived Workload” (OPW) worksheet was also used, the additional row which also has the OPW worksheet results was added to the table. The additional row shows the difference between OPW and the overall mean (without OPW). The percentage proportion of the TLX dimensions was rounded to the nearest decimal place; however, in a few cases, the percentage proportion was rounded to two decimal places.

The ‘Revised workload rating scale’

The ‘Revised workload rating scale’ presented in Table 4-4 was applied to the median values of the overall workload scores, and is presented in the last column in the tables featuring the overall workload score.

Workload data

The rest of this section will present the following data for each core team member per site:

- Tables with the overall workload scores showing the number of cases ("n"), minimum values, maximum values, mean, median, Standard Deviation (SD), and the workload level after the application of the 'Revised workload rating scale'; note that 'Overall Perceived Workload' (OPW) worksheet was administered to Radiation oncologists and Radiologists, therefore OPW scores are included, as well as the average OPW median value, and the difference between the average median value and OPW (in %).
- Tables showing the percentage proportion of each TLX dimension: Mental Demand (MD, Physical Demand (PD), Temporal Demand (TD), Performance (PE), Effort (EF), and Frustration (FR). The pie charts representing the dimensions for each core team member for each operation are presented in the Appendix D.

Data analyses on perceived workload are presented in Appendix C. Data analyses, including pie charts of the TLX dimensions, are presented in Appendix D. Overall perceived workload scores box plots and dimension proportions histograms are presented in Appendix E.

Site 1

Radiation oncologist

Table 4-6 Site 1: Overall workload scores and "Overall Perceived Workload" (OPW) scores for Radiation oncologist

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
1	TRUS placement	10	13	31	20.03	19.33	6.35	Low
2	Measure volume	11	15	45	25.33	24.66	7.94	Low
3	Needle implantation	11	17	69	40.69	39.33	17.15	Moderate
4	Volume post needle	10	16	36	25.33	23.83	7.05	Low

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
5	Virtual prostate and urethra positioning	9	13	29	19.81	19.33	5.45	Low
6	Peripheral seeding and planning	11	16	40	28.18	29.66	7.97	Moderate
7	Central seeding and planning	11	20	42	29.94	30.00	7.05	Moderate
Average median value						26.59		
OPW	Overall perceived workload	11	21	54	35.78	34.66	9.90	Moderate
The difference between the average median value and OPW (in %)						23.28		

Table 4-7 Site 1: The percentage proportion of the TLX dimensions for Radiation oncologist

Operation number	MD	PD	TD	PE	EF	FR
1	24.2	18.0	10.7	20.9	24.0	2.2
2	16.5	10.5	31.0	17.0	22.2	2.9
3	7.2	17.3	28.1	9.4	23.7	14.3
4	15.9	5.2	23.0	19.0	24.9	12.2
5	32.3	10.6	6.6	21.9	24.8	3.9
6	10.9	18.9	32.0	13.8	21.5	3.0
7	32.9	7.9	17.0	14.8	23.7	3.7
OPW	15.5	16.5	34.6	7.5	21.5	4.5
Overall mean (without OPW)	20.0	12.6	21.2	16.7	23.5	6.0
The difference between OPW and the overall mean (without OPW)	4.5	3.9	13.4	9.2	2.0	1.5

Medical physicist #1

Table 4-8 Site 1: Overall workload scores for Medical physicist #1

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
1	QA of the source activity	11	11	56	41.71	43.00	12.10	Moderate
2	Measure volume	9	9	61	45.07	49.66	14.56	High (acceptable)
3	Volume post needle	11	44	55	50.78	48.00	6.22	Moderate

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
4	Peripheral plan verification	11	38	58	50.42	50.00	6.12	High (acceptable)
5	Estimate central needle positioning and seed implantation	11	42	60	50.42	50.00	6.12	High (acceptable)
6	Final verification (dosimetry)	11	37	65	48.69	49.33	7.04	Moderate
7	Room monitoring / contouring – no source left	10	5	53	31.43	35.33	15.04	Moderate

Table 4-9 Site 1: The percentage proportion of the TLX dimensions for Medical physicist #1

Operation number	MD	PD	TD	PE	EF	FR
1	33.3	5.5	16.4	9.0	34.9	1.0
2	34.6	7.1	27.6	9.3	20.4	0.9
3	32.0	7.3	25.2	8.5	22.6	4.5
4	32.1	7.2	25.8	6.3	22.4	6.2
5	35.3	5.5	26.5	5.0	24.9	2.8
6	34.1	5.0	22.8	5.2	26.6	6.4
7	31.9	16.8	18.3	9.7	22.0	1.4
Overall mean	33.3	7.8	23.2	7.6	24.8	3.3

Medical physicist #2

Table 4-10 Site 1: Overall workload scores for Medical physicist #2

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
1	QA of the source activity	11	9	60	40.49	45.66	16.87	Moderate
2	Room monitoring / contouring – no source left	8	5	43	30.75	33.33	11.62	Moderate
3	Seeds evaluation form	11	8	47	30.24	41.33	16.93	Moderate

Table 4-11 Site 1: The percentage proportion of TLX dimensions for Medical physicist #2

Operation number	MD	PD	TD	PE	EF	FR
1	32.2	10.0	30.3	5.7	18.2	3.7
2	34.4	4.5	16.1	10.8	33.0	1.2
3	33.3	12.9	16.4	10.4	27.0	0.0
Overall mean	33.3	9.1	21.0	9.0	26.0	1.6

Nurse

Table 4-12 Site 1: Overall workload scores for the Nurse

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
1	Patient setup	9	36	59	49.03	51.66	8.70	High (acceptable)
2	Seeding	8	27	84	51.93	52.47	15.66	High (acceptable)

Table 4-13 Site 1: The percentage proportion of the TLX dimensions for the Nurse

Operation number	MD	PD	TD	PE	EF	FR
1	27.2	22.1	30.3	4.1	15.1	1.2
2	42.3	7.9	18.8	4.3	26.6	0.1
Overall mean	34.8	15.0	24.5	4.2	20.9	0.6

Anaesthetist

Table 4-14 Site 1: Overall workload scores for Anaesthetist

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
1	Patient setup	10	18	55	33.26	30.00	12.70	Moderate
2	Patient monitoring	10	11	51	22.66	17.16	13.50	Low

Table 4-15 Site 1: The percentage proportion of the TLX dimensions for Anaesthetist

Operation number	MD	PD	TD	PE	EF	FR
1	48.0	2.0	11.9	14.4	12.5	11.5
2	47.8	2.6	5.6	22.5	13.0	8.5
Overall mean	47.9	2.3	8.7	18.4	12.7	10.0

Site 2

Radiation oncologist

Table 4-16 Site 2: Overall TLX workload scores and "Overall Perceived Workload" (OPW) scores for Radiation Oncologist

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
1	TRUS placement	15	2	59	21.69	15.33	16.32	Low
2	Measure volume	15	0	22	10.83	9.00	6.82	Low
3	Needle implantation	15	16	63	36.37	30.00	15.39	Moderate
4	Volume post needle	15	3	33	13.60	12.33	7.85	Low
5	Virtual prostate and urethra positioning	15	0	64	9.99	7.33	15.56	Low
6	Peripheral seeding and planning	15	0	48	30.40	32.66	15.36	Moderate
7	Central seeding and planning	15	6	60	26.81	27.00	15.50	Low
8	Volume post implant	15	0	28	8.49	6.00	8.25	Low
Average median value						17.45		
OPW	Overall perceived workload	15	9	68	38.89	41.00	17.73	Moderate
The difference between the average median value and OPW (in %)						57.43		

Table 4-17 Site 2: The percentage proportion of the TLX dimensions for Radiation oncologist

Operation number	MD	PD	TD	PE	EF	FR
1	47.2	2.7	9.7	1.4	35.8	3.3
2	28.6	3.0	19.1	4.6	37.6	7
3	40.2	3.7	3.8	4.0	42.9	5.4
4	48.5	2.9	13.6	3.7	25.7	5.6
5	38.5	1.3	13.7	10.2	11.8	24.5
6	47.5	4.8	8.0	3.3	31.0	5.4
7	57.4	2.7	7.7	3.5	26.9	1.8
8	25.9	3.1	21.1	4.4	32.4	13.0
OPW	40.6	2.8	12.7	2.6	36.9	4.4
Overall mean (without OPW)	41.7	3.0	12.1	4.4	30.5	8.2
The difference between OPW and the overall mean (without OPW)	1.1	0.2	0.6	1.8	6.4	3.8

Medical physicist #1

Table 4-18 Site 2: Overall workload scores for Medical physicist #1

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
1	QA of the source activity	14	17	69	32.47	28.33	14.72	Low
2	Measure volume	16	14	72	32.66	29.67	15.57	Moderate
3	Volume post needle	16	11	68	36.37	38.00	14.98	Moderate
4	Peripheral plan verification	15	27	79	48.84	49.00	15.39	Moderate
5	Estimate central needle positioning and seed implantation	15	20	79	50.09	48.00	18.16	Moderate
6	Final verification (dosimetry)	16	21	85	51.58	50.67	19.40	High (acceptable)
7	Room monitoring / contouring – no source left	8	11	39	29.21	30.17	8.41	Moderate

Table 4-19 Site 2: The percentage proportion of the TLX dimensions for Medical physicist #1

Operation number	MD	PD	TD	PE	EF	FR
1	31.1	5.6	25.6	17.4	17.3	3.0
2	26.2	2.3	26.9	13.9	18.7	11.9
3	25.6	2.1	26.6	12.0	19.2	14.6
4	30.8	1.4	18.9	11.0	21.2	16.7
5	27.8	1.1	22.3	12.0	20.8	16.1
6	33.7	2.9	16.4	12.5	19.6	15.0
7	12.0	22.6	25.1	19.7	15.4	5.1
Overall mean	26.7	5.4	23.1	14.1	18.9	11.8

Medical physicist #2

Table 4-20 Site 2: Overall workload scores for Medical physicist #2

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
1	QA of the source activity	14	24	71	37.19	32.33	14.22	Moderate
2	Room monitoring / contouring – no source left	14	13	76	36.47	32.00	20.71	Moderate
3	Seeds evaluation form	16	13	81	42.02	40.17	15.97	Moderate

Table 4-21 Site 2: The percentage proportion of the TLX dimensions for Medical physicist #2

Operation number	MD	PD	TD	PE	EF	FR
1	30.8	6.7	23.7	17.0	13.8	8.0
2	8.4	20.4	31.3	20.9	16.5	2.4
3	30.2	1.5	30.2	14.2	15.7	8.2
Overall mean	23.2	9.5	28.4	17.4	15.3	6.2

Nurse

Table 4-22 Site 2: Overall workload scores for the Nurse

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
1	Patient setup	14	29	76	49.73	46.00	15.63	Moderate
2	Seeding	14	28	67	47.95	47.17	11.09	Moderate

Table 4-23 Site 2: The percentage proportion of the TLX dimensions for the Nurse

Operation number	MD	PD	TD	PE	EF	FR
1	19.5	14.5	27.1	15.9	22.6	0.5
2	28.3	13.0	24.4	10.3	22.9	1.0
Overall mean	23.9	13.75	25.75	13.1	22.75	0.75

Anaesthetist

Table 4-24 Site 2: Overall workload scores for Anaesthetist

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
1	Patient setup	13	5	53	32.79	35.33	14.58	Moderate
2	Patient monitoring	13	5	49	21.97	19.66	12.26	Low

Table 4-25 Site 2: The percentage proportion of the TLX dimensions for Anaesthetist

Operation number	MD	PD	TD	PE	EF	FR
1	25.1	6.8	22.0	17.6	21.6	6.9
2	26.9	6.4	17.1	24.2	18.2	7.2
Overall mean	26.0	6.6	19.6	20.9	19.9	7.0

Site 3

Radiation oncologist

Table 4-26 Site 3: Overall workload scores and "Overall Perceived Workload" (OPW) for Radiation Oncologist

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
1	TRUS placement	10	5	17	7.93	5.00	4.65	Low (acceptable)
2	Measure volume	10	4	13	6.10	5.00	2.64	Low (acceptable)
3	Needle implantation	9	5	16	7.74	7.00	3.74	Low
4	Volume post needle	7	4	17	6.57	5.00	4.77	Low (acceptable)
5	Virtual prostate and urethra positioning	10	3	41	9.90	5.00	11.63	Low (acceptable)
6	Peripheral seeding and planning	10	5	28	10.43	7.33	7.94	Low
7	Central seeding and planning	10	5	54	14.47	8.67	15.39	Low
Average median value						6.14		
OPW	Overall perceived workload	9	5	28	9.52	5.00	7.88	Low (acceptable)
The difference between the average median value and OPW (in %)						22.8		

Table 4-27 Site 3: The percentage proportion of the TLX dimensions for Radiation oncologist

Operation number	MD	PD	TD	PE	EF	FR
1	9.9	20.1	31.7	24.6	13.7	0.0
2	9.6	22.5	33.8	21.8	12.0	0.4
3	10.9	28.3	25.4	21.5	13.9	0.0
4	12.9	23.4	33.9	19.9	10.0	0.0
5	9.8	14.4	33.9	19.9	19.7	2.4
6	10.1	33.6	22.2	16.1	19.1	0.0
7	13.5	23.9	24.9	16.0	21.8	0.0
OPW	13.9	15.1	31.6	19.4	19.9	0.0
Overall mean (without OPW)	10.9	23.7	29.4	19.9	15.7	0.4
The difference between OPW and the overall mean (without OPW)	3.0	8.6	2.2	0.5	4.2	0.4

Medical physicist #1

Table 4-28 Site 3: Overall workload scores for Medical physicist #1

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
1	QA of the source activity	10	6	49	21.43	21.17	14.78	Low
2	Measure volume	10	10	37	20.03	16.00	9.16	Low
3	Volume post needle	10	5	49	23.93	19.33	15.45	Low
4	Peripheral plan verification	10	8	59	28.90	23.16	15.72	Low
5	Estimate central needle positioning and seed implantation	9	6	70	34.81	35.33	19.44	Moderate
6	Final verification (dosimetry)	8	12	55	30.75	26.17	13.08	Low
7	Room monitoring / contouring – no source left	10	8	40	18.53	17.00	10.05	Low

Table 4-29 Site 3: The percentage proportion of the TLX dimensions for Medical physicist #1

Operation number	MD	PD	TD	PE	EF	FR
1	22.5	4.8	23.2	15.4	28.7	5.6
2	32.0	0.4	35.3	13.2	13.6	5.6
3	28.5	2.1	33.1	11.1	16.7	8.7
4	35.6	1.1	33.9	7.2	15.9	6.5
5	42.0	0.0	27.9	7.6	15.7	6.8
6	42.2	1.0	25.9	10.7	13.1	7.2
7	21.1	18.6	25.6	13.1	13.0	8.6
Overall mean	32.0	4.0	29.2	11.2	16.6	7.0

Medical physicist #2

Table 4-30 Site 3: Overall workload scores for Medical physicist #2

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
1	QA of the source activity	10	10	48	21.83	16.50	13.71	Low
2	Room monitoring / contouring – no source left	5	5	49	19.73	14.33	17.59	Low
3	Seeds evaluation form	10	5	52	29.00	29.50	19.36	Low

Table 4-31 Site 3: The percentage proportion of the TLX dimensions for Medical physicist #2

Operation number	MD	PD	TD	PE	EF	FR
1	29.8	1.5	31.5	13.8	17.1	6.5
2	18.2	11.6	19.9	13.5	32.8	4.0
3	27.8	8.7	22.2	12.1	22.0	7.3
Overall mean	25.2	7.2	24.5	13.1	24.0	6.0

Nurse

Table 4-32 Site 3: Overall workload scores for the Nurse

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
1	Patient setup	5	13	64	39.66	37.00	21.67	Moderate
2	Seeding	3	26	54	40.22	14.00	13.84	Low

Table 4-33 Site 3: The percentage proportion of the TLX dimensions for the Nurse

Operation number	MD	PD	TD	PE	EF	FR
1	9.1	22.8	26.9	6.7	33.3	1.2
2	44.2	4.3	9.0	13.3	15.8	13.3
Overall mean	26.7	13.6	18.0	10.0	24.5	7.2

Anaesthetist

Table 4-34 Site 3: Overall workload scores for Anaesthetist

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
1	Patient setup	1	50	50	50.00	50.00	NA	High (acceptable)
2	Patient monitoring	1	50	50	50.00	50.00	NA	High (acceptable)

Table 4-35 Site 3: The percentage proportion of the TLX dimensions for Anaesthetist

Operation number	MD	PD	TD	PE	EF	FR
1	34.0	27.0	13.0	13.0	13.0	0.0
2	34.0	27.0	13.0	13.0	13.0	0.0
Overall mean	34.0	27.0	13.0	13.0	13.0	0.0

Site 4

Radiation oncologist

For a better understanding, a timeline of operations performed by Radiation oncologist & Radiologist, and Medical physicist #1 & Medical physicist #2 are presented in Figure 3-5.

Table 4-36 Site 4: Overall workload scores and "Overall Perceived Workload" (OPW) for Radiation oncologist

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
1	Catheter placement & ultrasound positioning	10	8	22	12.96	12.17	3.63	Low
4	Assess plan	10	14	44	21.86	16.83	9.57	Low
5	Seed placement	10	13	69	25.06	18.00	16.82	Low
7	Assess implant	10	12	27	15.70	14.67	4.30	Low
Average median value						15.41		
OPW	Overall perceived workload	10	11	64	20.67	16.00	15.61	Low
The difference between the average median value and OPW (in %)						3.68		

Table 4-37 Site 4: The percentage proportion of the TLX dimensions for Radiation oncologist

Operation number	MD	PD	TD	PE	EF	FR
1	13.3	35.6	3.6	11.0	36.4	0.0
4	54.8	3.6	3.0	8.0	30.6	0.0
5	25.3	38.7	1.9	7.2	27.0	0.0
7	51.0	5.3	3.1	8.9	31.7	0.1
OPW	36.9	25.9	1.9	9.2	25.5	0.6
Overall mean (without OPW)	36.1	20.8	2.9	8.8	31.4	0.0
The difference between OPW and the overall mean (without OPW)	0.8	5.1	1.0	0.4	5.9	0.6

Radiologist

Table 4-38 Site 4: Overall workload scores and "Overall Perceived Workload" (OPW) for Radiologist

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
2	Refine the position, volume study & image acquisition	10	10	12	10.63	10.33	0.63	Low
3	Contouring	10	13	30	18.76	16.00	5.74	Low
6	Seed placement	10	17	34	31.87	34.00	5.31	Moderate
7	Assess implant	10	12	27	15.70	14.67	4.30	Low
Average median value						18.75		
OPW	Overall perceived workload	10	11	64	20.67	16.00	15.61	Low
The difference between the average median value and OPW (in %)						17.18		

Table 4-39 Site 4: The percentage proportion of the TLX dimensions for Radiologist

Operation number	MD	PD	TD	PE	EF	FR
2	17.8	14.8	31.8	15.0	20.7	0.0
3	18.7	5.2	30.4	9.8	36.0	0.0
6	43.5	12.3	6.7	17.1	20.5	0.0
7	51.0	5.3	3.1	8.9	31.7	0.1
OPW	36.9	25.9	1.9	9.2	25.5	0.6
Overall mean (without OPW)	32.7	9.4	18.0	12.7	27.2	0.0
The difference between OPW and the overall mean (without OPW)	4.2	16.4	16.1	3.5	1.7	0.6

Medical physicist #1

Table 4-40 Site 4: Overall workload scores for Medical physicist #1

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
1	Equipment setup & patient data	10	5	49	22.37	22.33	16.38	Low
2	Volume study	9	7	28	14.29	11.66	7.42	Low
3	Plan & plan printing	9	19	66	49.15	55.00	15.71	High

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
								(acceptable)
5	Real time check	9	5	32	18.85	14.33	9.77	Low
6	Seed placement & needle positioning	9	11	62	38.11	49.00	20.23	Moderate
7	Final plan verification (Dosimetry)	9	10	44	24.92	26.66	12.26	Low

Table 4-41 Site 4: The percentage proportion of the TLX dimensions for Medical physicist #1

Operation number	MD	PD	TD	PE	EF	FR
1	25.1	10.1	29.0	12.3	19.5	4.1
2	21.3	3.3	48.7	13.8	12.3	0.6
3	40.8	0.2	31.4	8.4	17.9	1.2
5	28.3	0.8	37.3	15.4	14.1	4.1
6	39.6	1.3	31.8	10.1	14.8	2.3
7	39.2	2.2	27.3	15.0	14.6	1.7
Overall mean	32.4	3.0	34.2	12.5	15.6	2.3

Medical physicist #2

Table 4-42 Site 4: Overall TLX workload scores for Medical physicist #2

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
4	Prepare the needles, seed calibration & prepare the seeds	10	12	54	33.70	30.67	15.16	Moderate
8	Room monitoring	10	30	80	54.07	48.67	17.91	Moderate

Table 4-43 Site 4: The percentage proportion of the TLX dimensions for Medical physicist #2

Operation number	MD	PD	TD	PE	EF	FR
4	41.2	1.8	31.3	0.0	22.1	3.7
8	11.1	0.7	55.6	0.9	14.1	17.7
Overall mean	26.1	1.2	43.4	0.5	18.1	10.7

Nurse

Table 4-44 Site 4: Overall workload scores for the Nurse

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
1	Patient setup	8	5	76	40.87	46.17	24.70	Moderate
2	Needle loading report	5	5	52	32.40	37.66	19.14	Moderate

Table 4-45 Site 4: The percentage proportion of the TLX dimensions for the Nurse

Operation number	MD	PD	TD	PE	EF	FR
1	14.6	29.7	20.9	11.4	23.1	0.1
2	26.8	4.0	17.0	30.9	21.4	0.0
Overall mean	20.7	16.9	19.0	21.1	22.25	0.05

Anaesthetist

Table 4-46 Site 4: Overall workload scores for Anaesthetist

Operation		N	Min.	Max.	Mean	Median	SD	Workload level
1	Patient setup	9	11	48	25.33	29.46	11.21	Low
2	Patient monitoring	8	11	60	29.46	26.00	18.93	Low

Table 4-47 Site 4: The percentage proportion of the TLX dimensions for Anaesthetist

Operation number	MD	PD	TD	PE	EF	FR
1	22.7	3.6	37.8	9.2	25.7	1.0
2	32.3	3.3	31.3	8.7	23.1	1.3
Overall mean	27.5	3.5	34.5	9.0	24.4	1.1

4.4.2 A summary of TLX scores

A summary of TLX scores represents a descriptive summary of the overall workload scores after the application of the 'Revised workload rating scale', presented in Table 4-4. The summary helps with identification of the red-line values per core team member per site (there were four hospital sites in total).

Table 4-48 A summary of TLX scores

Core team member	**Workload level**	**Site**
Radiation oncologist	Low-Moderate Low (Acceptable) – Low Low	1, 2 3 4
Radiologist	Low - Moderate	4
Medical physicist #1	Moderate – High (Acceptable) Low – Moderate – High (Acceptable) Low - Moderate	1 2, 4 3
Medical physicist #2	Moderate Low	1, 2, 4 3
Radiation oncology nurse	High (Acceptable) Moderate Low - Moderate	1 2, 4 3
Anaesthetist	Low – Moderate High (Acceptable) Low	1, 2 3 4

4.4.3 Summaries of TLX dimensions

This section presents two summaries of the TLX dimensions:

a) A summary of TLX dimensions is presented in Table 4-49. The values represent TLX dimensions for each individual core team member separately across four sites and all operations together. Please note that in the first row, in the second column, the N=5 because the operations of Radiation oncologist & Radiologist at the fourth site were merged together; refer to the timeline in Figure 3-5. Also, the percentage values were rounded to the nearest decimal place.

b) The radar charts were created to visually present the TLX workload data together. Five radar charts present the data for each core team member across four sites: Figure 4-2, Figure 4-3, Figure 4-4, Figure 4-5 and Figure 4-6. Please note that in the first radar chart, the Radiologist is labelled as “Site 4 / Radiologist”.

Table 4-49 Percentage values of the summarised TLX dimensions

Team member	**N**	**MD**	**PD**	**TD**	**PE**	**EF**	**FR**
Radiation oncologist & Radiologist	5	28.3	13.9	16.7	12.5	25.7	2.9
Medical physicist #1	4	31.1	5.0	27.4	11.4	19.0	6.1
Medical physicist #2	4	27.0	6.8	29.3	10.0	20.8	6.1
Nurse	4	26.5	14.85	21.85	12.1	22.6	2.1
Anaesthetist	4	32.7	9.9	19.7	15.4	17.8	4.5

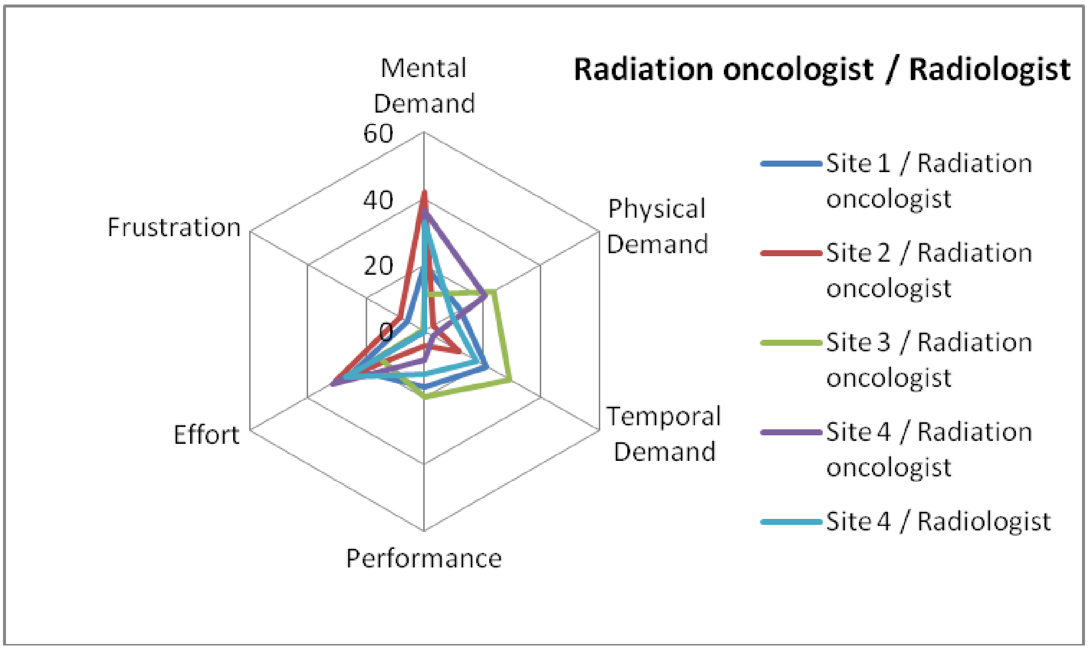


Figure 4-2 Radar chart of TLX dimensions for Radiation oncologists / Radiologists

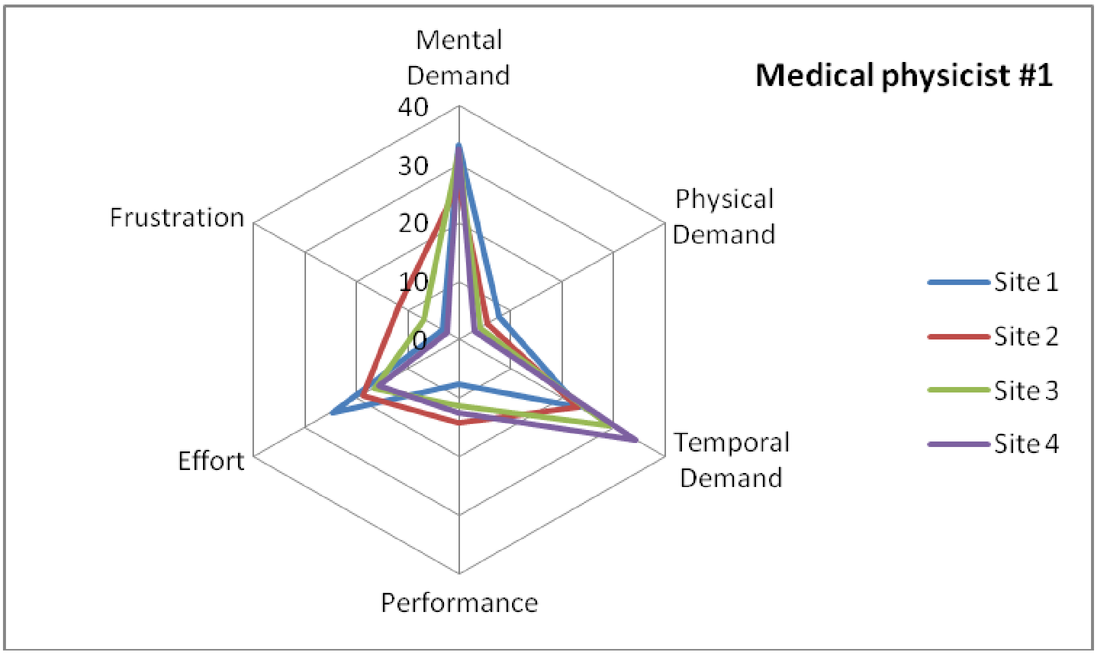


Figure 4-3 Radar chart of TLX dimensions for Medical physicists #1

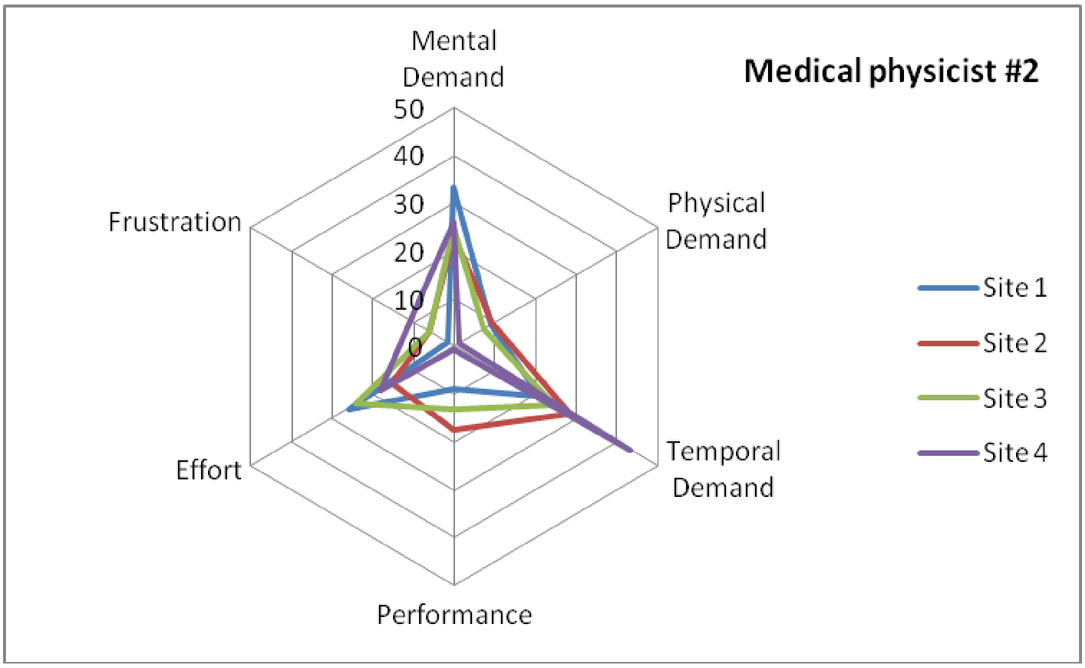


Figure 4-4 Radar chart of TLX dimensions for Medical physicists #2

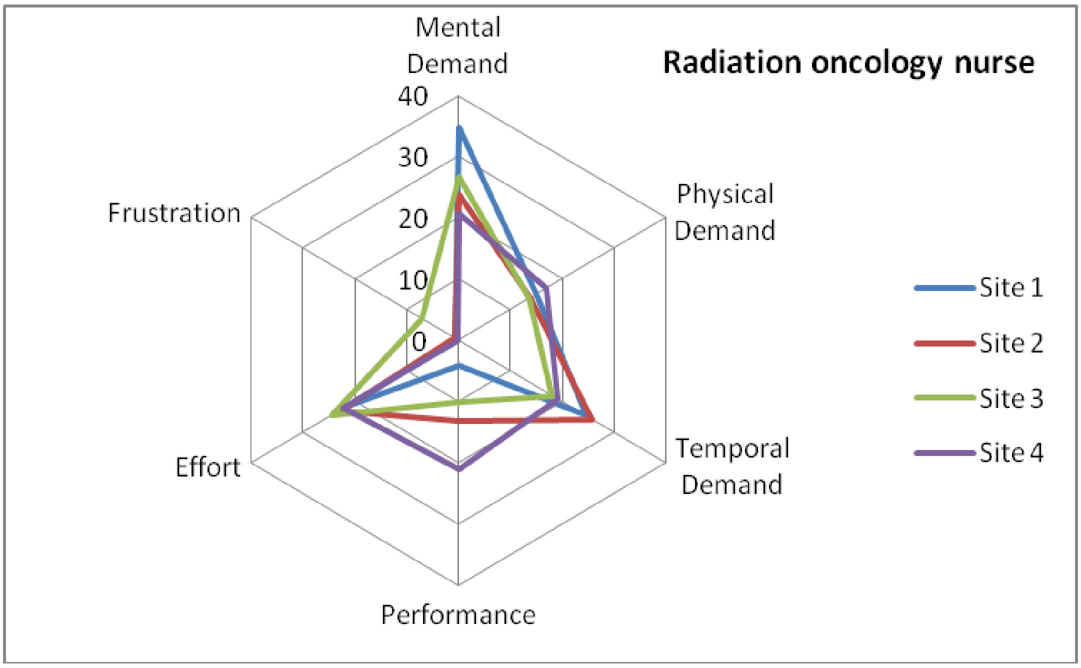


Figure 4-5 Radar chart of TLX dimensions for Radiation oncology nurses

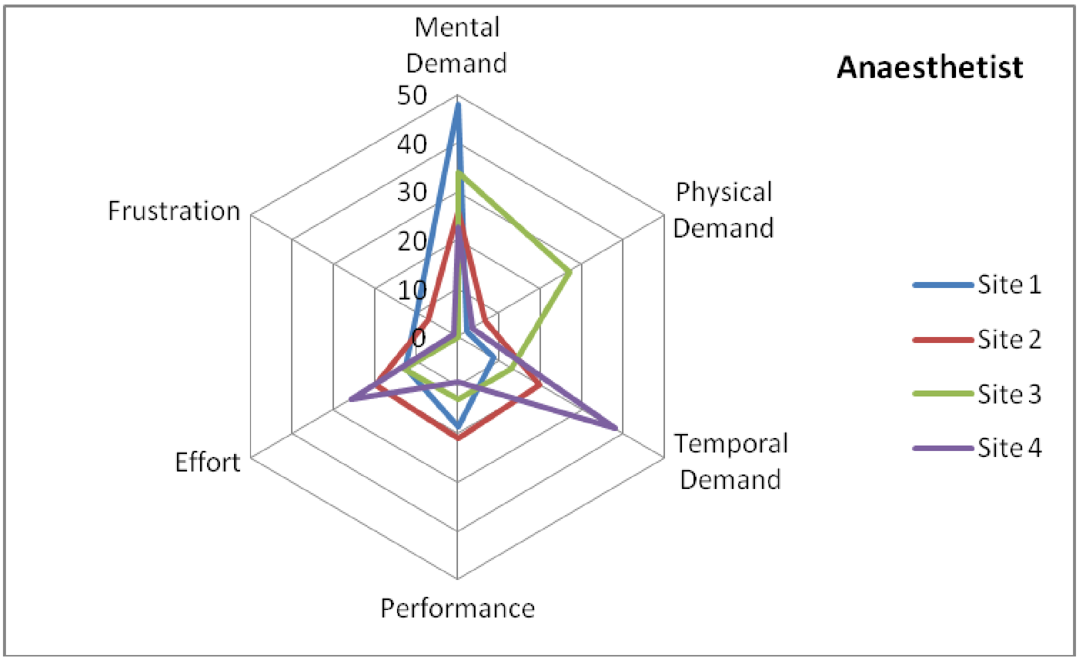


Figure 4-6 Radar chart of TLX dimensions for Anaesthetists

4.4.4 The "Overall workload score" compared to the "Overall Perceived Workload" (OPW) values

The "Overall Perceived Workload" (OPW) worksheets were administered to Radiation oncologists and Radiologists on all four sites to assess the overall workload of all operations as one. The OPW scores were then compared to the average median scores of the "Overall Workload Score" originally calculated by following the NASA-TLX instructions by Hart and Staveland (1988), and the method described in the section 4.3.2 *Calculating the overall workload score and dimensions contribution*. By comparing the "Overall Perceived Workload" (OPW) and the "Overall Workload Score" the difference between the two techniques should be shown; should a single worksheet be administered to assess the workload rather than a series of individual TLX worksheets administered for each operation. The results in the following tables have shown differences in the range of 2.81% to 57.43%: Table 4-6, Table 4-16, Table 4-26, Table 4-36 and Table 4-38. Therefore it is recommended to administer individual TLX worksheets to assess the workload because they are more precise and more detailed rather than a single "overall" worksheet that would assess everything at the same time.

4.4.5 Critical levels of perceived workload

Four steps listed at the end of the section 4.3.6 *'The 'Revised workload rating scale'* were followed to tackle the critical levels. The workload scores between zero and 5 were assessed as a "low" red-line, corresponding to when the workload can be "too low"; the workload scores between 50 and 55 were assessed as a "high" red-line, corresponding to when the workload can be "too high". A summary of red-line values in LDR prostate brachytherapy is presented in Table 4-50. Furthermore, the reported red-line data was researched for its *consistency* and *frequency* to evaluate if the workload categories were "acceptable" or "unacceptable". Because none of these two factors was present, the red-line workload values were all marked as "acceptable".

Table 4-50 A summary of the red-line values in LDR prostate brachytherapy data

Site	Role	Operation		N	Median	Red-line	
1	Medical physicist #1	2	Measure volume	9	49.66	High	Acceptable
1	Medical physicist #1	4	Peripheral plan verification	11	50.00	High	Acceptable
1	Medical physicist #1	5	Estimate central needle positioning and seed implantation	11	50.00	High	Acceptable
1	Nurse	1	Patient setup	9	51.66	High	Acceptable
1	Nurse	2	Seeding	8	52.47	High	Acceptable
2	Medical physicist #1	6	Final verification (dosimetry)	16	50.67	High	Acceptable
3	Radiation oncologist	1	TRUS placement	10	5.00	Low	Acceptable
3	Radiation oncologist	2	Measure volume	10	5.00	Low	Acceptable
3	Radiation oncologist	4	Volume post needle	7	5.00	Low	Acceptable
3	Radiation oncologist	5	Virtual prostate and urethra positioning	10	5.00	Low	Acceptable
3	Anaesthetist	1	Patient setup	1	50.00	High	Acceptable
3	Anaesthetist	2	Patient monitoring	1	50.00	High	Acceptable
4	Medical physicist #1	3	Plan & review printing	9	55.00	High	Acceptable

4.4.6 Observational data and observational notes

Observational data

The agreement with each hospital site was to collect the information on the patient's prostate gland volume, average number of seeds delivered, average number of needles used, and average seed activity. The data was collected at the "Treatment delivery" stage in four hospitals in Ireland which perform the LDR brachytherapy. The data is summarised in Table 4-51; note that "n" stands for the number of cases with the valid data.

Table 4-51 A summary of data taken during the observation of LDR prostate brachytherapy activities of four hospitals in Ireland

Brachytherapy details	**Site**			
	1	**2**	**3**	**4**
Prostate volume (cc)	30.5 (n=11)	32.28 (n=16)	39.70 (n=10)	41.43 (n=10)
Average number of seeds delivered	66.18 (n=11)	62.76 (n=17)	79.5 (n=10)	57.7 (n=10)
Average number of needles used	17.72 (n=11)	15.21 (n=14)	20.3 (n=10)	18.8 (n=10)
Average seed activity (mCi)	0.466 (n=11)	0.393 (n=17)	0.42 (n=10)	0.396 (n=10)

Observational notes

The agreement with each hospital site was also to take observational notes at the "Treatment delivery" stage of the LDR prostate brachytherapy treatment. The notes were taken before, during and after the collection of the TLX data by the researcher. The purpose of the notes was to write down any human-automation issues that would arise during the LDR prostate brachytherapy treatment, with a brief description of the cause of these issues, e.g. issues with long and narrow prostate gland, public arch interference, issues with TRUS, etc. The notes are presented in Table 4-52. The table includes the "location" and the "description" of those issues, e.g. prostate gland, urethra, TRUS, etc. The individual notes from each site are presented in Appendix B.

Table 4-52 A summary of the observational notes taken during the observation of LDR prostate brachytherapy activities at four hospitals in Ireland

Location	**Issue description**
Gland	Volume: Big, small
Gland	Asymmetry: Left, right
Gland	Shape: Narrow, wide, broad, long, short, asymmetric, odd, unusual
Gland	Gland enlarged
Gland	Gland spongy
Gland	Gland shifts
Fibrosis	Present
Cist	Present
Urethra	Length, shape
Urethra	Moved
Pubic arch interference	High apex
Bone interference	From the side
Seeds	Loose seeds, moving seeds, warm seeds
Applicator	Stiff handle, cartridge stuck
Cartridge	Seeds stuck
Patient	Limited leg mobility
Patient	Full bladder
Patient	Injury in the past
TRUS and computer connection	Interrupted, lost, no view
TRUS	Operating system freezing & reset

4.5 Discussion

4.5.1 The main findings of this chapter

The main findings of this chapter are presented below. Perceived workload was assessed amongst the core team members at the 'Treatment delivery' stage across four hospital sites in Ireland performing LDR prostate brachytherapy treatment by using the NASA-TLX method. Critical workload levels were identified amongst the core team members after the application of the 'Revised workload rating scale' and the 'Red-line' criteria, as presented in Table 4-50: TLX scores of 50-51 for Medical physicist #1 on sites 1, 2 and 4, TLX score of 52-53 for Nurse on site 1, TLX score of 5 for Radiation oncologist on site 3, and TLX score of 50 for Anaesthetist on site 3. The levels were high (or low, like in the case of Radiation oncologist), but "still acceptable". The remaining text in this chapter will discuss the results more specifically.

4.5.2 Perceived workload and NASA-TLX

Perceived workload was assessed by using the paper-based NASA-TLX among the LDR prostate brachytherapy team members in four different hospitals in Ireland. NASA-TLX has been applied to many different areas in the past, such as aviation, air traffic control, military, aerospace, nuclear industry, operating rooms, rail industry, teleoperation, space application, healthcare, etc. (Hart 2006; Lane, Stanton et al. 2006; Balfe, Sharples et al. 2015). In 2012 it was still described as "*one of the best methods for workload measurement*" (Satterfield, Ramirez et al. 2012). It is a widely recognised, accepted, and a highly reliable method (Karwowski 2007), it is easy to administer (Wilson and Corlett 2005), and it can be used to "*obtain more detailed and diagnostic data*" (Hill, Iavecchia et al. 1992). For more details about the NASA-TLX refer to sections 3.3.9 – 3.3.11 of this thesis.

The TLX worksheets were administered to each core team member individually straight after the LDR treatment was over, assessing their main operations (or "tasks"), as identified in the previous chapter: Radiation oncologist, Radiologist, Medical physics team (referred to as “Medical physicist #1” and “Medical physicist #2”), the Nurse, and Anaesthetist. TLX worksheets were applied to both, “loose seeds” or “stranded seeds” LDR brachytherapy. Table 3-5, Table 3-6, Table 3-7, Table 3-8, and Table 3-9 present operations at “loose seeds” LDR brachytherapy. Table 3-10, Table 3-11, Table 3-12, Table 3-13, Table 3-14 and Table 3-15 present operations at “stranded seeds” LDR prostate brachytherapy where TLX worksheets were administered. The TLX worksheets administered to the “Radiation oncologist” in three hospital sites and to the “Radiologist” in one hospital site had an additional TLX worksheet to assess the “Overall workload score” of all operations. These additional TLX worksheets in the “Results” section are called “Overall Perceived Workload” (OPW), and should not be confused with the term “overall workload score”, which is a term for a workload score calculated on each TLX worksheet, following the NASA-TLX method by (Hart and Staveland 1988). The additional OPW TLX worksheet was used to compare the OPW result against the average workload values from each operation. This will be explained in more details later on in this chapter.

Overall, the NASA-TLX method itself was very straightforward, it was easy to understand, and it required very little training. In addition, it did not take a lot of time for the team members to fill the TLX worksheets out.

The challenges of NASA-TLX

The challenges of NASA-TLX presented below further expand on the challenges discussed by Galičič et al. (2013) and also represent the perceived workload research limitations:

- The familiarity with the TLX worksheet: The core team members had to be familiar with the content and layout of the worksheet before they filled it out. Clear instructions were given, and all questions were answered beforehand. It was ensured that the core team members were comfortable enough with filling out each worksheet.
- The TLX worksheet administration: It was not always possible to administer

the TLX worksheets straight after each operation, because the LDR brachytherapy procedure was ongoing, because of time constraint (the treatment is performed while the patient is anaesthetised), and because the team members were gowned up (they were wearing aprons, hair nets, shoe protection, gloves, etc.).

- Filling out the TLX worksheet at a later date: Usually each core team member filled out the applied TLX worksheet straight after the LDR brachytherapy treatment was finished. Although the TLX worksheets were sometimes filled out at a later stage due to personal obligations, e.g. other treatments, meetings, other patients, etc., this, however, did not happen very often.
- Administration of the TLX worksheets in the clinical environment: The LDR prostate brachytherapy treatment is performed in the clinical environment, where the patient is anaesthetised. The core team members are gowned-up, and are wearing surgical gloves, etc. They are under time pressure, and have to perform the treatment process undisturbed, without any external interruptions. Administering TLX worksheets after a single operation would be disruptive to their working process and could compromise their performance.
- Personal bias when filling out the TLX worksheets: Because the worksheets measure objective (perceived) workload, it is possible that individuals intentionally or unintentionally influence the workload results by scoring the TLX levels differently according to their perception, or by avoiding one or more TLX dimensions when filling out the pair-wise comparison tiles. However, these issues were not noted during the administration of the TLX worksheets in this research.
- Personal factors: Workload can be perceived differently by each individual person. The quality of the reported scores depends on the person’s skills, knowledge, other tasks, time pressure, as well as training, years of experience, and personality. The scores are therefore not obsolete, but still give a value of the perceived workload at a certain point in time on a certain operation performed. It is important to assess perceived workload with a large enough group, and to correctly calculate mean and median values in order to apply the ‘Revised workload rating scale’ which categorises the workload

into low, moderate, high, and to identify issues that need to be addressed when the workload is “too low” or “too high”. However, in order to completely validate the perceived workload scores, these would have to be combined with other, perhaps physiological measurements, e.g. muscle movements, heart rate, eye blink rate, etc., to justify the findings. Although measuring physiological workload may raise additional application challenges of the clinical environment.

- Errors when filling out the TLX worksheets: Due to human nature, and even with the best intentions, errors when filling out the worksheets occurred, e.g. missing values on the dimension scale(s), missing pair-wise comparison tile(s). Such worksheets were marked as “invalid” and were not included in the statistical analysis since it was impossible to calculate the overall workload score with the missing data.
- The methodology behind calculating workload rating scores: The original Hart and Staveland (1988) method describes that workload rating scores are calculated by taking the results from the six scales, one for each dimension, and multiplying them with the number of times dimensions appeared after the pair-wise comparison. However, some researchers stated that “the weighting procedure of TLX is superfluous and can be omitted without compromising the measure” (Stanton, Hedge et al. 2004). Removing the pair-wise comparison tiles would change the original method of calculating the average workload to a simple calculation of an arithmetic mean of the obtained scores (Stanton, Hedge et al. 2004).
- The validity of the workload constructs: The workload constructs including NASA-TLX were questioned by De Winter (2014) who stated that “*human factors constructs are situated towards the operational end of the representational-operational continuum*” and that such constructs aim to predict an empirical reality, not neglect it (De Winter 2014). However, a lot of time went into developing NASA-TLX and its constructs (Hart and Staveland 1988), and questioning the validity of these constructs would challenge a number of carefully developed and selected perceptive and cognitive models developed by psychologists and engineers over the last few decades.

- Focus on individual cases, and not on the median values of the TLX scores: Focusing on individual cases with extreme minimum or maximum values may uncover interesting facts about perceived workload. However, focusing on such cases may look like chasing after something else, and could miss the purpose of assessing perceived workload as part of the *optimal* performance. This, however, would be different if the research was specific enough and applied to finding the relationship between perceived workload and other aspects in particular cases, e.g. emergency cases or extreme cases, when the patient safety is compromised.

A number of these challenges can be omitted with the presence of the researcher in the clinical environment, e.g. the familiarity with the TLX worksheet, the correct TLX administration, avoiding errors when filling out the worksheet. However, not all issues can be avoided, e.g. personal bias, personal factors, etc. A few new challenges arose with the overall workload scores and critical workload levels. These challenges are discussed in the next section.

Workload rating scale and its challenges

The 'Workload rating scale' was developed with the purpose of presenting different stages of workload, that is, when the workload is low, moderate or high (Galičič, Fallon et al. 2013). The TLX levels can be assessed on the scale between 0 and 100, and then if divided by three, the scale of presenting low, medium and high workload would change in increments of 33.33. Based on the collected data, the levels of "low" workload can be anything between zero and 33.33. It is similar for "moderate" workload levels because they represent values between "low" and "high" workload levels. However, the exact "high" workload TLX score was never discussed by the original authors (Hart and Staveland 1988; Hart 2006). "High" workload may be described as workload that is very high for the user, but is still manageable in a short period of time. In terms of safety, it would still be deemed as "acceptable". Hart (2006) also mentions that the "high" workload may be "too" high at some point, but does not discuss how the too high workload is evident from the TLX scale or TLX results. However, the workload rating scale of 55 or higher was determined as "high" based on the previous research done by Mazur et al. (2012), among others. The challenge was, however, to discover the “critical” levels behind the “high” workload. This is often referred to as the “red-line” of workload, when the “high” workload is “too high” (Grier, Wickens et al. 2008).

Critical workload levels

The accepted workload levels fluctuate from low, moderate to high. However, the issue of when “high” workload is “too high” in NASA-TLX method has only been briefly mentioned by Hart (2006). The “red-line” issue was further discussed by Grier *et al.* (2008) and NASA (2010). A “too high” workload level would mean that there is a serious decrease of human performance and that such level is not acceptable. Such tasks should be researched further especially in terms of their consistency and frequency, and other contributing factors that could compromise an operator’s performance. Other contributing factors are personal characteristics (e.g. experience, training, and education), technology (e.g. ‘automation’), the environmental factors (e.g. humidity, lighting, clinical space constrictions), job demand (e.g. time pressure, lack of staff, posture, etc.), etc.

Tackling the “red-line” criteria

The red-line does not mean a particular task is unacceptable for performing, although (NASA 2010) would argue otherwise: that red-line is the cut-off point at which the workload is “unacceptable”. Therefore, rather than acting as a cut-off point, the red-line should act as an indicator of a “problem” occurring in terms of performance. The “problem” may still be “acceptable”, or if assessed otherwise, it could be “unacceptable”. A good example is a comparison of the red-line to an engine tachometer. The engine performance decreases if the operator drives the engine over the red-line frequently or for a very long time (Reid and Colle 1988).

In terms of workload, the red-line criteria should not only focus on the “high” workload, but also on the “low” workload. Therefore, the red-line criteria for two workload “extremes” was applied to the ‘Workload rating scale’ previously developed by Galičič *et al.* (2013). The first extreme is when the workload is “too low” and the second extreme is when the workload is “too high”. When the values “cross” the red-line, they fall into the range where they should be inspected further if they are “acceptable” or “unacceptable”. The tasks should be inspected for their frequency and consistency.

In Merriam-Webster online dictionary (Merriam-Webster.com 2015) *frequency* is defined as “*the number of repetitions of a periodic process in a unit of time*”.

In The Free Dictionary (Thefreedictionary.com 2015) *consistency* is defined as the “*Agreement or logical coherence among things or parts*”.

If one of these two factors was present in this research study, other contributing factors should also be researched. Only when these criterions are completely exhausted, should these values be changed from “acceptable” to “unacceptable”. Nevertheless, the criterions should not be applied universally to any job, but should fit to a specific job and its factors, e.g. the job type, job demands, levels of education, work experience, training, etc. If the task is unacceptable, then a further review of the task might be required to identify the contributors identified with NASA-TLX, as well as the root cause(s) of such a workload level. This includes identifying the sub-task(s) where such scores were reported, as well as inspecting the TLX contributing factors, e.g. TLX dimensions. A check-list example of the red-line criteria for the Radiation Oncologist is presented in the Appendix F. The list includes ergonomics and general occupational health & safety issues, and is not exhaustive. Specific applied methods could also be used, e.g. Rapid Upper Body Assessment, Rapid Entire Body Assessment, Hand Activity Level, Root Cause Analysis, etc.

A comparison of tackling the red-line is a standard health & safety risk assessment. In risk assessment, the risk is assessed by the means of likelihood and severity. The operation is assessed as safe when the risk is kept low or moderate, and is deemed “acceptable”. However, if any of those two factors increases, the risk can quickly become high and “unacceptable” and further investigation is needed to mitigate the risk. If the operation is assessed as unsafe due to a number of different contributing factors that add to the high likelihood or severity, then further investigation is necessary immediately to handle such risks. Similarly, if the red-line values are assessed as “high”, then further investigation is needed to mitigate such levels.

Therefore, in terms of risk, the workload assessed as “too low” or “too high” (and still acceptable) can be compared to “Medium” risk. The workload assessed as “too low” or “too high” (and still unacceptable) can be compared to “High” risk.

Applying the ‘Revised workload rating scale’

The red-line criteria were incorporated into the ‘Revised workload rating scale’. Five brackets for the workload levels were introduced: “Too low”,” Low”, “Moderate”, “High” and “Too high”. The revised workload rating scale is presented in detail in Table 4-4.

After the mean and median values for the overall workload scores were calculated for the core team members at “loose seeds” and “stranded seeds” LDR brachytherapy for four sites in Ireland, the ‘Revised workload rating scale’ was applied to the median workload values. The median workload values were chosen over the mean values because the mean values included outliers in the data, and were slightly different to median values due to the high data range between minimum and maximum values. The ‘Revised workload rating scale’ scores were applied to all of the data collected on the workload across four hospital sites in Ireland.

Below is an overview of the applied ‘Revised workload rating scale’ to workload median values for:

- Radiation oncologist: The workload reported was “low” or “moderate”. On site #3 it was assessed as “low (acceptable)” at the following operations: “1 - TRUS placement”, “2 - Measure volume”, “4 - Volume post needle”, “5 - Virtual prostate and urethra positioning”.
- Radiologist: The workload reported was “low” and “moderate”. No high workload ratings were reported.
- Medical physicist #1: The workload reported was “low” and “moderate”. It was assessed as “high (acceptable)” at “3- Volume post needle” operation on site #4, and at the operation “6 - Final verification (dosimetry)” on site #2.
- Medical physicist #2: The workload reported was “low” or “moderate”. No

high workload ratings were reported.

- Nurse: The workload reported was "low" or "moderate". On site #1 it was assessed as "high (acceptable)" at both operations: "1 – Patient setup", and "2 – Seeding".
- Anaesthetist: The workload reported was "low" or "moderate". On #3 it was assessed as "high (acceptable)" at both operations: "1 – Patient setup", and "2 - patient monitoring".

A summary of the red-line values is presented in Table 4-50 in the Results section of this thesis. The results were checked for *frequency* and *consistency*. An example of *frequency* and *consistency* would mean that the data appears often in each treatment case, and for the same problem to be found, the output of the data is the same. In our case, the frequency factors were not present because all operations only appeared once, and not frequently. The consistency factors were also not present either because there was no logical coherence among the data. Therefore, since neither of those factors was present, no further investigation was necessary, and no "unacceptable" red-line values were found. The workload values identified for when the workload was "too low" or "too high" were all "acceptable".

NASA-TLX in numbers

NASA-TLX scores were calculated by following the Hart and Staveland (1988) method, described in the Methods section of this thesis. The scores are presented for each core team member separately across all four sites. The main operations were identified in the previous chapter by using Hierarchical Task Analysis. The TLX scores represent a numerical value on a scale between zero and one hundred. For easier interpretation of the values, refer to the 'Revised workload rating scale' presented in Table 4-4.

Note that for the Radiation oncologists across the four hospital sites and for the Radiologist at one hospital site, the "Overall Perceived Workload" (OPW) was also assessed as a separate additional TLX worksheet to compare it against the average median values of all assessed operations.

The remainder of this section discusses the results presented in the section 4.2.7. It discusses the overall workload scores, and the TLX dimensions for each core team member separately. Note that sites 1-3 were performing “loose seeds” LDR prostate brachytherapy, and site 4 was performing “stranded seeds” LDR prostate brachytherapy.

<u>Radiation oncologists and Radiologists</u>

The workload scores for Radiation oncologists (sites 1-4) and Radiologists (only at site 4) varied between “Low” and “Moderate” at all four sites after the application of the 'Revised workload rating scale'. The workload scores at site 3 had very low average score of 5, which was categorised as “low” after the application of the ‘Revised workload rating scale’. The workload scores were reported as the lowest (but still acceptable) at the following operations:

- “1 - TRUS placement”: It is usually not a highly demanding operation, but it requires a good set of skills to set up the stepper, preparing TRUS, and connecting it correctly in order to get good quality feedback on the ultrasound monitor. This included a small amount of physical activity.
- “2 - Measure volume”: It might have been assessed low because it was easy to set up the visual feedback to highlight the urethra on the ultrasound, once catheterisation of the patient was performed. The Radiation oncologist’s sub-operations help the Medical physicist #1 to set up the visual feedback with their own specialised software.
- “4- Volume post needle” and “5 - Virtual prostate and urethra positioning”: Low scores may reflect the high skill set of the Radiation oncologist, familiarity with the procedure, their experience and expertise. Or, it may be that they were just rated low because it was perceived as low. It was observed that these operations were performed under time pressure, and required a good eye-hand coordination to optimise TRUS feedback for more optimal performance.

It was expected that the workload would be the highest among the Radiation oncologists, but surprisingly this was not the case. On one hand, the results reported low workload levels, which may be due to high skill sets, extensive knowledge of the subject, familiarisation with the procedure, with the technology, and the large amount of experience of the Radiation oncologist. On the other hand, they may have been perceived as low workload. There were a few issues that arose during the LDR prostate brachytherapy treatment, which were noted in the observational notes, and were addressed immediately. They were all related to the prostate gland, e.g. oddly shaped prostate gland, wide prostate gland, long and narrow prostate gland, large and asymmetric prostate gland, prostate gland shape changed once the needles were inserted, high apex, etc. In one case urethra slightly moved during the needle insertion, but that did not result in increased workload. In another case, the ultrasound cable was trapped under the patient's bed, but that was dealt with quickly and it did not increase workload. And in the third case, the Mick® applicator was stiff, and had to be changed with another Mick® applicator. This however, did not result in an increased workload.

Other similar research in this field did not report low TXL scores, like in our research but, on the contrary. Mazur et al. (2012; Mazur, Mosaly et al. 2013) reported high TLX scores of >40 for Radiation oncologists at EBRT "Treatment planning" stage. Compared to our research, the highest workload score assessed was 39.33, which was categorised as "Moderate" after the application of the 'Revised workload rating scale'. This may be because the two radiation treatments are completely different, each with their own unique sets of operations and sub-operations. It may also be that the EBRT is much more demanding for Radiation oncologists, and it would be interesting to see the results of the workload assessment at EBRT "Treatment planning" stage in Ireland. Mazur et al. (2013) also reported that performance started to decline at ≥ 55, and suggested the score of 55 was acknowledged "as a potential workload limit". The TLX dimension contributions, however, were not mentioned (Mazur, Mosaly et al. 2013). The top three TLX dimensions in our research were MD, EF, PE, which were the same top three TLX dimensions as in the research by Mazur et al. (2012). The similarity may reflect the nature of the job and consequently the Radiation oncologist's operations and sub-operations, but it may not necessary reflect their workload levels.

Similarly, in another research study, Mazur et al. (2014) were assessing workload and errors during the EBRT “Treatment planning” stage. The TLX scores ranged between 6.67 and 72.33 among 27 observed cases. The authors noted that the performance started to decline at TLX score above 50. They also reported that the MD was a “major source of the overall TLX score”, but also added, that their research was performed in a simulated environment, and that the research performed in a clinical setting may have produced different results (Mazur, Mosaly et al. 2014). Compared to our study, MD was also the major contributor to the overall TLX dimension proportion, and based on the analysis, MD is one of the TLX dimensions which is predominant amongst Radiation oncologists in radiotherapy.

Medical physicist #1

The workload for Medical physicist #1 varied between “Low”, “Moderate” and “High” (but still acceptable) across all 4 sites after the application of the 'Revised workload rating scale'. The highest, but still acceptable average TLX scores of 50 were reported at:

- “2 – Measure volume” (site 1) operation: this operation requires a big amount of details and focus, especially with synchronising the computer with the ultrasound, setting up grids and margins on the computer, capturing prostate edges, marking organs at risk, etc. It is one of the core operations Medical physicist #1 has to perform, and requires a good knowledge of the specialised software, as well as recognising patterns and edges from TRUS, as well as strong communication skills when working closely with the Radiation oncologist.
- “4 - Peripheral plan verification” operation (site 1): it requires a high level of focus and very little or no distractions from the fellow team mates. It is crucial to follow the peripherally implanted seeds on the computer, to insert a virtual seed by using the software program, as well as to check for isodosis of the implanted seeds.
- “5- Estimate central needle positioning and seed implantation” operation (site 1): it requires a set of excellent computer skills in order to present a 3D virtual model of the prostate, to insert a virtual seed implantation in the centre of the prostate gland, and to check the isodosis of the implanted seeds on an

ongoing basis.

- "6 – Final verification (dosimetry)" operation (site 2): This operation may be rated high due to the mental pressure put on the Medical physicist during the operation. They need to get the 3D imaging correctly in order to present an even isodosis of the radioactive seeds, and this may be sometimes challenging mostly due to the shape of the prostate gland, if it is for e.g. skewed, narrow, long, small, large, etc. However, it can also be challenging because of the issues with the technology: in one case, it was observed that the cable between the ultrasound and the computer resulted in a glitchy picture; in a few cases, the cable connection between the ultrasound and the computer was loose, and it resulted in bad images on the computer. In another case, the seeds were slightly (7%) "warmer" than they should be. However, all issues were dealt with, and did not result in an increased workload. Medical physicists receive an extensive training which cover all the above mentioned scenarios in detail.
- "3 – Plan & plan printing" operation (site 4): Similar to "loose seeds" brachytherapy, this operation may require the Medical physicist to have high precision skills, knowledge and experience, especially when it comes to decision making on the number of seeds and needles that need to be implanted into the prostate gland.

There are many different reasons for high reported workload scores: they may be assessed as high because of personal characteristics, e.g. Medical physicists perceive their workload as higher because of the nature of the job, the operations and sub-operations they have to perform, time constraints, work stress, etc. The issues which appeared during the LDR prostate brachytherapy treatment were either related to the prostate gland, or had to do with the human-automation interaction.

In similar research, high workload was also reported among the Medical physicists at EBRT "Treatment planning" stage by Mazur et al. (2012), who reported the workload scores higher than 50. Similarly to the Radiation oncologist, it may be that the assessed workload scores in EBRT are higher than the workload scores in LDR prostate brachytherapy. In another research by Galičič (McGrath, Madden et al. 2012), a subjective workload assessment of the Medical physicist was assessed with

NASA-TLX during their monthly Linac QA. The workload results did not report high workload results, but resulted in high levels of TD, PE and FR, which due to the nature of the QA operations and sub-operations may have correctly reflected the workload assessment. The top three TLX dimensions in our research were MD, TD and EF, which match the TLX dimensions presented by Galičič (McGrath, Madden et al. 2012), without the higher percentage of FR as in the research involving the Linac QA. This also indicates that MD and EF of the Medical physicist's operations and sub-operations in our research are the same as the TLX dimension among the Medical physicists and Radiation therapists in the research performed by Mazur et al. (2012).

Medical physicist #2

The average workload scores were categorised as "Low" (site 3) and "Moderate" (sites 1, 2 and 4) after the application of the 'Revised workload rating scale'. The operations required high numeric skill set (especially at "1 - QA of the source activity" and "3 – Seeds evaluation form" at "loose seeds" LDR prostate brachytherapy), as well as knowledge of the treatment, training and experience. No specific issues were found that would specifically relate to this operation. However, in case something went wrong, and any of the radioactive sources were found around the patient and in the operating theatre during the "2 - Room monitoring / contouring" operation, they would create a higher risk to the patient and other core team members, and would therefore be reflected as higher workload. The "3 - Seeds evaluation form" operation had a large range between scores (13-81). The operation may have been scored incorrectly, based on the differences in personal perception of workload, or maybe the scores reflected some difficulties during the operation, which were not noted by the researchers. The three TLX dimensions with the highest proportion were TD, MD and EF, and almost mirrored the TLX dimensions assessed by Medical physicist #1.

Radiation oncology nurse

The workload scores were categorised as "High" (but still acceptable) at site 1 for both operations, whereas at the other sites, it was categorised as "Low" (site 3) and

“Moderate (sites 2-4) after the application of the ‘Revised workload scale’:

- An average TLX score of >50 at “1 – Patient setup” operation may have been high because the operation was physically demanding, because it was directly dealing with the patient, e.g. escorting the patient to the operating theatre, lifting the patient onto the operating table (with the help of other core team members and the support staff), preparing the materials for the treatment, and assisting Radiation oncologist with ad-hoc sub-operations.
- The second operation, “2 - Seeding”, requires high focus and requires good vision, because the radioactive seeds need to be counted correctly under an artificial lamp. It also requires a number of hand movements, e.g. preparing the Mick® applicator, discarding the empty seed cartridges and needles into the assigned sharps bin, as well as strong verbal communication, e.g. calling out the number of seeds counted, which is picked up by the Radiation oncologist and both Medical physicists. This workload would most probably be even higher if something went wrong, e.g. the number of seeds counted did not match the number of seeds implanted into the prostate gland by the Radiation oncologist, or the number of seeds recorded on the "Seeds evaluation form" by Medical physicist #2.

The workload scores are similar to research by Mosaly et al. (2010), who assessed the subjective workload of Radiation oncology nurses in the HDR brachytherapy treatment, which is a little bit different treatment modality to LDR prostate brachytherapy treatment. Nevertheless, the workload scores were mostly categorised as “Moderate” and in some cases as “High” (even higher than 55) (Mosaly, Xu et al. 2010). These high workload scores can confirm that the workload assessed as part of this research is similar to workload levels related to brachytherapy at another hospital site in a different country. However, high levels of perceived workload among Nurses were recorded only at one site in our study, whereas it was assessed as moderate in other sites. The highest proportion of the TLX dimension in our research weas at MD, EF and TD, which reflects the nature of Nurse’s operations and sub-operations.

Anaesthetist

Apart from a single assessment reporting a “High” workload level at site 3, the workload assessed by the anaesthetists was reported as “Low” (sites 1, 2, and 4) and “Moderate” (sites 1 and 2) after the application of the 'Revised workload rating scale' at the following operations:

- “1 – Patient setup”: this operation requires a lot of physical and mental effort by the Anaesthetist because of correctly setting up the patient, checking for the patient's allergies, reactions, preparing the drugs, anaesthetising the patient, etc.
- “2 – Patient monitoring”: this operation puts Anaesthetist in the supervisory role, once all the technologies are connected, and patient's functions are stable. This workload level would be higher if Anaesthetist would have to interfere with the LDR prostate brachytherapy treatment, which would only happen if the patient’s health was compromised. But since these cases are very rare, the workload was assessed as “Moderate”.

No particular issues were found in the observational notes for both operations, and this may be reflected in the assessed levels of workload. As mentioned above, if any issues arose, related to the patient during the LDR prostate brachytherapy treatment, Anaesthetist’s workload would consequently increase in order to preserve the patient’s safety. The highest proportion of the TLX dimensions reported was MD, TD, and EF.

General comment to the discussion of the TLX results and TLX dimension proportions

The results from the above comparative studies are interesting and informative, but cannot be directly compared to our study. The first reason is that the workload was assessed at EBRT radiotherapy and HDR brachytherapy, which are both totally different treatment modalities to LDR prostate brachytherapy, and include completely different sets of operations and sub-operations, different team member’s roles and responsibilities, specific training, etc. The second reason is that most of the above studies were performed in a simulated environment, which may give, as one study suggests (Mazur, Mosaly et al. 2013), slightly different results as if the studies were performed in a real clinical environment; like in our research. However, what can be compared, is some similarity of the NASA-TLX results and TLX dimensions, the applicability of the NASA-TLX method as a successful quantitative method of assessing perceived workload in all the above mentioned radiotherapy environments, the application of TLX assessments highlighted workload score of 50 or above among specific team members, e.g. Radiation oncologists, Nurses, or Medical physicists, and a TLX score above 50 as a workload level after which the performance decreases (Mosaly, Xu et al. 2010; Mazur, Mosaly et al. 2013; Mazur, Mosaly et al. 2014). Furthermore, no particular issues that would affect the patient safety during the LDR prostate treatment brachytherapy were found, apart from the small issues mentioned above, which were recorded in the observational notes. No critical levels of perceived workload were found despite low and high levels appearing at some of the core team's operations. Our research contributed to addressing and understanding the perceived workload in LDR prostate brachytherapy and to identifying critical workload levels in LDR prostate brachytherapy which could compromise patient safety.

A summary of TLX scores

A summary of TLX scores presented in Table 4-50 summarises workload levels that were assessed as "safety critical" after the application of the 'Revised workload rating score' for each core team member per site. What had to be investigated further was the operation scenarios where the workload was "too low" or "too high", meaning in the range between 0 and 5 (for "low"), and between 50 and 55 (for "high)". For Radiation oncologist, this occurred in Site 3, when the median was 5, which means "low", but still "acceptable" at the following operations: "1 – TRUS placement", "2 – Measure Volume", "4 – Volume post needle", and "5 – Virtual prostate and urethra positioning". The workload for Medical physicist #1 was reported to be high in Site 1 at "2 – Measure Volume", "4 - Peripheral plan verification", and "5 – Estimate central needle positioning and seed implantation" operations. Similarly, for Medical physicist #1 in Site 2, the workload was reported as "moderate", and very close to "high" at "4 – Peripheral plan verification" and "high", but still "acceptable" and "6 – Final verification (dosimetry)" operations. In Site 4, the workload for the Medical physicist #1 was reported "moderate", and almost "high" at "3 – Plan & plan printing" and "6 – Seed placement & needle positioning" operations. In Site 1, the workload for the Radiation oncology nurse was assessed as "high", but still "acceptable" for both operations, "1 – Patient setup" and "2 - Seeding". Despite workload being assessed as "high", but still "acceptable" for Anaesthetist in Site 3, this cannot be valid due to the single returned TLX workload sheet. Nevertheless, most of the operations highlighted in here involve interaction with the technology, which will be assessed further in the next few chapters, where the relationship between the perceived workload and 'Levels of automation' will be researched further.

A summary of TLX dimensions

After analysis of the proportion of the TLX dimensions, it is interesting to observe, that different core team members reported on different proportion of the TLX dimensions for their operations. Even though some of the operations are interconnected, the core team member's roles and responsibilities are different, as it was presented in Section 3.4.1 and discussed in Section 3.5.3. The highest three proportions of the TLX dimension proportions for Radiation oncologist were MD, EF, followed by TD, for Medical physics team were TD, MD and EF, for Radiation oncology nurse were MD, EF and TD, and for Anaesthetist were MD, TD and EF. Generally, the levels of FR across all disciplines and all sites were very low. For a more detailed analysis of the TLX dimensions refer to the individual discussion which covered each core team member per site, along with their roles and responsibilities.

Addressing the research questions

Two research questions were addressed:

1. The critical workload levels: critical perceived workload levels are levels when the perceived workload is "too low", or "too high". In terms of perceived workload, this was identified after the application of the 'Revised workload rating

scale', which highlighted the categories that may fall in the 'Red-line' values. After researching the data for its *consistency* and *frequency*, the red-line values were assessed as "acceptable".

2. The core team members' operations and the critical perceived workload levels: The operations where the critical perceived workload levels appeared are presented in Table 4-50. These included operations of Radiation oncologists, Medical Physicist #1, Radiation oncology nurses, and Anaesthetists. Most of the operations involved interaction with the technology; that is the interaction with the automation, with the exception of Radiation oncology nurses at "Patient setup" operation, which was predominantly a physical operation.

4.5.3 Future work and recommendations to assessing perceived workload in LDR prostate brachytherapy

Future work and recommendations to assessing perceived workload in LDR prostate brachytherapy may include analysis and techniques, which are beyond the scope of the research presented in this thesis:

- The use of NASA-TLX in electronic format may accelerate data collection, data analysis and reduce immediate errors, such as missing pair-wise comparison tiles, e.g. an electronic version of NASA-TLX on a tablet. However, this would not be able to reduce personal familiarisation with the method, personal bias, etc., because it would still remain a subjective method.
- Combining perceived workload assessment with physiological measurements: the technology is developing fast; the devices are getting smaller, and more affordable. This includes specialist equipment that could more easily fit the limited space in the operating theatre, or specialist brachytherapy treatment room, e.g. portable heart rate monitors, ECG, EEG, eye blink rate devices or smart-phone applications, etc. This is expanded in more detail in Section 9.5.

4.6 Conclusions

Perceived workload data was collected from 48 LDR brachytherapy treatment cases at four different hospitals in Ireland by using the NASA-TLX method. The analysis of TLX worksheets produced an amazing amount of data (which resulted in the 1073 returned TLX worksheets), which was then analysed further to identify if the assessed operations were assessed as “too low”, or “too high”, and if they needed a further assessment under the “red-line” criteria, as these may compromise individual and team performance, and consequently, it may potentially compromise patient safety. The perceived workload data was presented individually, that is for each core team member’s main operation per site, and in a summarised version, which summarised data for core team members across the sites in terms of perceived workload scores. The workload dimension proportions collected from the TLX worksheet were analysed and presented separately. Almost every core team member at some point reported workload being “too low” or “too high”, and still “acceptable”.

The workload for Radiation oncologist at sites 1-3, which presented the “Loose seeds” LDR prostate brachytherapy, was assessed as low (but still acceptable) at most operations, but moderate at “Needle implantation” operation (sites 1-2), “Peripheral seeding and planning” operation (sites 1-2), and “Central seeding and planning” operation (site 1). The lowest workload reported was with a TLX score of 5 (out of 100) at site 3. The workload for Radiation oncologist and Radiologist at site 4, which presented the “Stranded seeds” LDR prostate brachytherapy, was low (but still acceptable) at all operations, except being “moderate” at Seeds placement” operation for Radiologist. This can be explained that despite demanding operations and sub-operations, Radiation oncologists and Radiologists had enough skills, knowledge and experience to be able to perform all the operations and sub-operations successfully. Their top three TLX dimensions were MD, EF and TD.

The highest workload reported was among Medical physicists and Radiation oncology nurses. The workload for Medical physicist #1 on sites 1-3 was assessed as low or moderate at “QA of the source activity”, low, moderate and high at “Volume post needle” operation, low or moderate at “Volume post needle” operation, low, moderate and high at “Peripheral plan verification” operation, moderate or high at “Estimate central needle positioning and seed implantation” operation, low, moderate and high at “Final verification (dosimetry)” operation, and low or moderate at “Room monitoring/contouring” operation. The highest (but still acceptable) workload was assessed at TLX score of 50-55 (out of 100) at sites 1 and 4. The workload for Medical physicist #1 on site 4 was assessed as low at most operations, except moderate at “Seeds placement & needle positioning” operation, and high (but still acceptable) at “Plan & plan printing” operation. The top three TLX dimensions for Medical physicist #1 were MD, TD and EF. Most of the workload results involved interaction with the technology, in particular an interaction with the specialised software for LDR prostate brachytherapy. Most of the issues with high workload reflected the issued with the equipment (e.g. glitchy software, issues with the TRUS cables, etc.), and could be easily solved. More specific issues would require improvement of the specialised software and further automation of the captured visual feedback from TRUS. This would change the levels of the perceived workload, and might require additional training and familiarisation with the updated or upgraded software.

The workload for Medical physicist #2 was assessed as moderate on sites 1, 3 and 4, and low on site 2 at all identified operations. The top three TLX dimensions for Medical physicist #1 were TD, MD and EF. The operations required strong numerical skills in order for the operations to be performed successfully.

The workload for the Radiation oncology nurse was low at site 1, low & moderate at site 3, moderate at sites 2 and 4, and high (but still acceptable) at site 1, which had teh TLX score of 50-52 (out of 100). The top three TLX dimensions for Nurse were MD, EF and TD. Most of the sub-operations at “Patient setup” required physical work, as well as effort in order to prepare everything that was required for the treatment. The second operation, “Seeding” required more mental effort, and helping the Radiation oncologist with needle and seed preparation.

The workload for Anaesthetist was assessed as low at site 4, and low-moderate at sites 1 and 2. The data collected at site 3 was assessed as high, but it only had one returned TLX worksheet. The top three TLX dimensions for Anaesthetist were MD, TD and EF. Similar to the Nurse, the patient setup required physical effort to set up the patient, as well as administering anaesthetic to the patient, whereas the role in the second operation was about supervising the process, and be prepared to intervene in case patient's life would be endangered.

After the perceived workload data was analysed and checked for red-line values identified in Table 4-50, no red-line values were identified, and all "low" and "high" perceived workload values were categorised as "acceptable" across all four sites. The highest workload reported was among Medical physicists and Radiation oncology nurses. As for the TLX dimensions, most of the TLX dimensions reported involved MD, TD and EF, which is not surprising for such a demanding clinical environment. Nevertheless, it is recommended that the perceived workload data is investigated further in terms of the relationship with the automation and 'Levels of automation' in the present system, which will be covered in the next few chapters.

This chapter addressed and answered two important research questions, presented earlier on in this thesis: "What are the critical levels of perceived workload among working professionals at the "Treatment delivery" stage of Low-Dose Rate prostate seeds brachytherapy treatment that could compromise patient safety?", and "Which core team members' operations do the critical perceived workload levels appear with?".

4.7 Chapter summary

This chapter introduced the definitions of workload, workload terminology, workload facts, issues and challenges, the importance of workload, and workload assessments in Radiotherapy and Brachytherapy. Furthermore, the chapter introduces one of the core topics of this thesis, perceived workload and NASA-TLX method for assessing the perceived workload, and its application to the main operations performed by the core team members of LDR prostate brachytherapy: Radiation oncologists, Radiologists, Medical physics team, Radiation oncology nurses, and Anaesthetists. It also introduced additional tools that can be applied after the perceived workload scores are obtained, such as the 'Workload rating scale' and the 'Revised workload rating scale', which categorise the perceived workload levels between “low”, “moderate”, and “high”. The latter also includes indicators of how and when to identify “red-line” values, which may identify if workload is “low” or “high” and “acceptable” or “unacceptable”. This chapter addressed and answered two research questions presented earlier on in this thesis. Further research is going to identify the relationship between the levels of perceived workload and ‘Levels of Automation’ for specific operations core team members performed.

Chapter 5: Automation and 'Levels of Automation' in Low-Dose Rate Prostate Brachytherapy

5.1 Chapter overview

This chapter introduces the topics of automation, 'Levels of Automation' and the issues with automation in more detail. It introduces the definitions and terms related to automation, 'levels of automation'. The main focus of this chapter is to present an overview of nine selected relevant 'Levels of Automation' models, and to provide the reasons behind the development of 'Modified Levels of automation' model for brachytherapy and LDR prostate brachytherapy. An example of 'Modified Levels of Automation' (MLOA) model for brachytherapy is presented, along with the reasons for modification, and research limitations. The MLOA model was applied to the main LDR prostate brachytherapy operations identified earlier in this thesis, which answered the third research question: "How can 'Modified Levels of Automation' be applied to Low-Dose Rate prostate brachytherapy?". The results of the application of MLOA will be used to research the relationship between perceived workload and 'levels of automation' and will be presented in one of the further chapters.

5.2 Introduction

5.2.1 The terms

In Merriam-Webster online dictionary (Merriam-Webster.com 2011), *automation* is defined as:

"1. The technique of making an apparatus, a process, or a system operate automatically.
2. The state of being operated automatically.
3. Automatically controlled operation of an apparatus, process, or system by mechanical or electronic devices that take the place of human labour"

Parasuraman & Riley (1997) defined automation as "*the execution by a machine agent (usually a computer) of a function that was previously done by a human*". Automation is also described as a "technology that actively selects, transforms information, makes decisions, or controls processes" and as such extends the human performance (Lee and See 2004). 'Levels of Automation' (LOA) can best be described as "*The concept which relates human and technology in the task allocation*" (Lindström and Winroth 2010).

5.2.2 Allocation of functions

"Allocation of functions" is applied to man-machine environments, where tasks for humans, machines, or between both are determined. The purpose of the allocation of functions is to improve and to maximise the overall systems performance (Czaja 1997). Any of the three elements can contribute to better performance, depending on the tasks and their stages. Tasks can be assigned to human, machine (often referred to as the "computer"), or both. It is very important to clarify the interaction between the man and machine, and also who is in control during the performed task. In complex operations, operations and sub-operations should be broken down to the level where there is no interaction between both of them anymore. At this level there is only a man or machine performing the task, and the LOA is assigned to either of them.

In 2006 edition of Reviews of Human Factors and Ergonomics, Sheridan and Parasuraman mentioned that the term "Human-Automation Interaction" was developed by Billings (1997), who wrote that "automation must be designed to work in conjunction with the humans controlling or otherwise interacting with" (Sheridan and Parasuraman 2005). Furthermore, the importance on which criteria to apply to automation varies from decision-and-control, reduce errors, job satisfaction, maintain the human as a final authority of automated systems, automation-related accidents, etc. (Sheridan and Parasuraman 2005).

5.2.3 An overview of the selected relevant 'Levels of Automation' models

Towards Safer Radiotherapy (2008) reported that typical system failures are changes in the treatment process, over-reliance on automated procedures, lack of training and competence issues for complex treatment modalities, poor design and documentation procedures (The Royal College of Radiologists, Society and College of Radiographers et al. 2008), amongst others.

A number of different methods for allocation of functions that apply to the LOA were developed in the past. Some aimed at the levels of automation in a mere "human-automation" relation, some included "Situation Awareness", some were developed for very specific environments (e.g., military, manufacturing, etc.). A quick overview of the selected relevant LOA models from 1978 to present is presented below:

1) "10-level and 8-level taxonomy for LOA" (Sheridan and Verplank 1978; Sheridan 2000)
2) "10-level taxonomy for LOA" (Endsley 1999)
3) "10-level taxonomy for LOA" (Sheridan 1997)
4) "A Model for Types and Levels of Human Interaction with Automation" (Parasuraman, Sheridan et al. 2000)
5) "Six stages of automation with assistance" (Wandke 2005)
6) "Function-Specific LOA and Automation (FLOOAT)" tool (Hart and Valasek 2007)
7) "Dynamo methodology" (Frohm 2008)
8) "Human-Automation Interaction" (Sheridan and Parasuraman 2005)
9) "Human-Automation Collaboration Taxonomy (HACT)" (Cummings and Bruni 2009)

i. 10-level and 8-level taxonomy for LOA

The 10-level LOA taxonomy was originally developed by Sheridan and Verplank in 1978, defining 10 levels of decision-making in man-computer interaction between human operators and underwater vehicles (Sheridan and Verplank 1978).

Ten levels by Sheridan and Verplank (1978) were described as:

(1) "Human does the whole job"
(2) "Computer helps determining options"
(3) "Computer helps determining options and suggests one, which human does not have to follow"
(4) "Computer selects an option and human chooses to use it or not"
(5) "Computer selects an action and selects it upon human approval"
(6) "Computer selects an action, human has enough time to stop it"
(7) "Computer does the whole job and lets human know what it was"
(8) "Computer does the whole job and lets human know only if human explicitly asks for it"
(9) "Computer does the whole job and decides what is told to the human"
(10) "Computer does the whole job" having the highest value"

More than 20 years later, Sheridan reviewed and simplified the 10-level LOA taxonomy into the 8-level taxonomy, resulting in (Sheridan 2000; Sheridan and Parasuraman 2005):

(1) "Human does all the work" having the lowest value
(2) "Computer suggests the alternative ways to the task"
(3) "Computer selects one way to do the task"
(4) "Computer executes the suggestion if human approves it"
(5) "Computer gives time to the human to execute an automatic execution "
(6) "Computer executes automatically, then necessarily informs human"
(7) "Computer executes automatically, then informs the human only if asked "
(8) "Computer selects the method, executes the task, and ignores the human"

To this 8-level LOA taxonomy Sheridan added a 4-stage model of human or machine processing (Sheridan 2000):

(A) “Acquire information”
(B) “Analyse and display”
(C) “Decide action”
(D) “Implement action”

Sheridan also provided a graphical example of LOA at different stages, incorporating LOA and the 4-stage model, which is very similar to the later work done with Parasuraman et al. (2000).

ii. 10-level taxonomy for LOA

Almost at the same time, Endsley and Kaber introduced a “10-level taxonomy for LOA” (Endsley 1999), where they incorporated the “original” 10-level LOA taxonomies from (Sheridan and Verplank 1978), and Endsley’s earlier work, related to Situation Awareness (Endsley 1988). According to Endsley’s earlier work, LOA could be applied to 5 different types of tasks (Endsley 1988):

(1) “Manual control”
(2) “Decision support”
(3) “Consensual Artificial Intelligence (AI)”
(4) “Monitored AI”
(5) “Full automation with no operator interaction”

The two joint methods resulted in a new 10-levels LOA taxonomy which can be assigned to human or computer, starting with level 1, and ending with level 10 (Endsley 1999):

(1) “Manual Control”
(2) “Action Support”
(3) “Batch Processing”

(4) "Shared Control"
(5) "Decision Support"
(6) "Blended Decision Making"
(7) "Rigid System"
(8) "Automated Decision Making"
(9) "Supervisory Control"
(10) "Full Automation"

These levels can be applied to four different roles of task performance:

(1) Monitoring
(2) Generating
(3) Selecting
(4) Implementing

This method was applied to the Air-traffic control simulation called "Multitask" at two different stages of LOA (Endsley 1999). Endsley's earlier work looked into LOA in "out-of-the-loop" performance and Situation Awareness of an operator in a simulated control task (Kaber and Endsley 1997). Since 2001 Endsley applied her research of Situation Awareness to different environments, such as Aviation, Military, Air Traffic Control, Unmanned Ground Vehicles, Medical, Power Systems, Homeland Defence, etc. (SA Technologies 2011).

iii. 10-level taxonomy for LOA

In 1997 Sheridan expanded Fitts' "Men are Better at – Machines are Better at" list (Fitts 1951) with his own model from 1978 (Sheridan 1997), and added two more dimensions to it, similar to his later work with Parasuraman et al. (2000). The two added dimensions presented in Table 5-1 were developed by Sheridan (1997):

a) The "Scale of LOA of Information acquisition and integration"
b) The "Scale of Degrees of Automation of Decision and action control"

iv. A Model for Types and Levels of Human Interaction with Automation

Parasuraman et al. (2000) developed "A Model for Types and Levels of Human Interaction with Automation", which featured levels from full automation (rated as "high" automation), to levels of manual operations (rated as "low" automation) on a 10-point scale:

(1) "Human makes all the decisions and actions, with no computer assistance"
(2) "Computer offers a complete set of decision/action alternatives"
(3) "Computer suggests one alternative"
(4) "Computer narrows the selection down to a few"
(5) "Computer executes the suggestion if the human approves"
(6) "Computer allows the human a restricted time to stop the automatic execution"
(7) "Computer executes automatically, then informs the human"
(8) "Computer only informs the human if asked"
(9) "Computer inform the human only if computer decides to"
(10) "Computer takes all the decisions, ignoring the human"

The 10 levels were applied to the 4-stages of information processing (also called "action stages") (Parasuraman, Sheridan et al. 2000):

(1) "Acquisition automation" (sensing input data);
(2) "Analysis automation" (involves cognitive functions; prediction over time);
(3) "Decision automation" (decision and action selection);
(4) "Action automation" (execution of selected actions).

This model can be applied to different work operations and sub-operations. The roles can be assigned between human, computer, or both. The LOA can also be presented in a graph with four stages of information processing, clearly showing low, medium and high LOA. This graph is an excellent example for visual representation of LOA.

Table 5-1 Two dimensional spaces to LOA model as per Sheridan (1997)

Information acquisition and integration	
Level	**Description**
1	The computer offers no assistance: the human must get all information
2	The computer suggests many sources of information, or
3	Narrows the sources down to a few, or
4	Guides the human to particular information, and
5	Responds to questions posed in restricted syntax, or
6	Responds to questions posed without restricted syntax, and
7	Integrates the information into a coherent presentation, or
8	Integrates the information into a coherent presentation, with an indication of confidence about each aspect, and
9	Passes it to human or automation for action, but allows for other consideration
10	The computer collects information as it sees fit, packages it, and presents it to human or automation for action with no opportunity to consider alternatives
Decision and action control	
Level	**Description**
1	The computer offers no assistance: the human must take all decisions and actions
2	The computer offers a complete set of decision/action alternatives, or
3	Narrows the sources down to a few, or
4	Suggests one alternative, and
5	Executes that suggestion if the human approves, or
6	Allows the human a restricted time to veto before automatic execution, or
7	Executes automatically, then necessarily informs the human, and
8	Informs the human only if asked, or
9	Informs the human only if it, the computer decides to,
10	The computer decides everything and acts autonomously, ignoring the human.

v. Six stages of automation with assistance

Wandke (2005) further developed Sheridan's and Parasuraman's systems into six action stages of Function allocation, taking into the account automation with assistance. A few examples of automated assistance are autopilot in aircraft cockpits, tracking assistance in cars, car breaking assistance, reading or audio assistance for handicapped users, automotive wheelchairs, etc. (Wandke 2005). The six stages developed by Wandke were:

(1) "Motivation. Activation and goal setting";
(2) "Perception";
(3) "Information integration, generating situation awareness";
(4) "Decision making, action selection";
(5) "Action execution";
(6) "Processing feedback of action results".

Each stage was divided into two sections: (1) "Social assistance", and (2) "Technical assistance". Social assistance usually involved additional person to assist the user (for e.g., coach in a football team, co-pilot in aircraft, guides, interpreters, secretaries, teachers, team work, etc.). Technical assistance was usually divided into further individual subsections, such as different warning systems, trouble-shooting systems, display assistance, screen readers, legends on the map, automated interpreter assistance, handbooks, operation instructions, electronic program guides for videos, navigation systems, automated air-conditioning, cruise controls, brake assistance, feedback assistance on a VCR, etc. (Wandke 2005). As there were different levels of assistance in place, it was difficult to assign the appropriate level of assistance to each stage. According to Wandke (2005), this creates additional dimension of "multiple" taxonomy with three approaches:

(1) "Customisation";
(2) "Adaptability";
(3) "Adaptation".

It had four levels:

(1) “Fixed assistance with “one size fits all” approach, which offers no flexibility”
(2) “Customised assistance, which is tailored to the specific user’s needs before the system is designed”
(3) “Adaptable assistance, which allow users to adjust the system to their specific needs by selection and tuning the parameters”
(4) “Adaptive assistance, where the adjustment is made by the system itself, with flexible parameters adaptable to the user (for e.g., eye tracker)”

Furthermore, assistance was divided into two types: (1) “Active assistance”, where assistance is initiated by the system, and (2) “Passive assistance”, where assistance is initiated by the user.

Wandke (2005) explains that some systems can also be combined, meaning, they can be active or passive, or active and passive, depending on the systems in use. He also talks about the use of different types of assistance in presentation media and its input modalities, such as:

(1) “Monomedia presentation, where single media is used for Human-Computer Interaction (HCI)”
(2) “Multimedia presentation, where the user has unlimited number of presentations (e.g., anthropomorphic characters)”
(3) “Implicit presentations, which are non-media presentations, where the user only experiences the assistance by its effects, and might not notice the assistance in the background”
(4) “Monomodal input, with manual controls, such as handling controls, typing, pointing, speaking, gesturing, etc.”
(5) “Multimodal input, where 2-3 or more modes are combined together to ask an assistance systems for support”
(6) “No explicit input, where active assistance systems separate autonomously and need no specific user input.”

The application of the taxonomy was tested by specifically developed software (Wandke 2005).

vi. Function-Specific LOA and Automation (FLOOAT) tool

Function-Specific LOA and Automation Tool (FLOOAT) (Hart and Valasek 2007), developed by National Aeronautics and Space Administration (NASA), looked into LOA and autonomy of each function of the Crew Exploration Vehicle (CEV). That is, into the interaction between the assigned responsibility between the crew and on-board computers of the CEV (Hart and Valasek 2007). FLOAAT tool has 4 levels of decision-making tasks: "Observe", "Orient", "Decide" and "Act" that can be applied to each task. To each of these tasks, levels of autonomy can be applied in 5 different levels, from 1 to 5; level 1 having complete ground authority, and level 5 having complete on-board authority. 8-scale LOA is applied as well, with level 1 having complete human authority, and 8 having complete on-board authority (Hart and Valasek 2007).

The results of the evaluation survey are converted to the LOA and autonomy scales, with the output showing the level of LOA and automation for each task or function observed. It helped to define LOA of the current system and to recommend LOA of the CEV by using FLOAAT tool. The difference was in 2 levels. Current system being at level 2, and described as "The human performs all ranking tasks, but the computer can be used as a tool of assistance", and the suggested FLOAAT level was at level 4, described as "Both, human and computer perform ranking tasks, the computer results are considered prime; potential implementation should include automated flight-mode based process which identifies which node is the best, with crew backup and override" (Hart and Valasek 2007).

vii. Dynamo methodology

Dynamo methodology is described in detail in Frohm's (2008) PhD thesis. It is an LOA methodology specifically developed for production systems (e.g. manufacturing plants), where there are many man-machine operations in place.

Dynamo method takes into consideration two categories in the man-machine system interaction: "Mechanical and equipment", and "Information and control". Based on that, 7 levels of automation can be identified for each category. Frohm's LOA model starts with the lowest level 1, and ends with the highest level 7.

The levels in the "Mechanical and equipment" category are:

(1) "Totally manual";
(2) "Static hand tool";
(3) "Flexible hand tool";
(4) "Automated hand tool";
(5) "Static machine/workstation";
(6) "Flexible machine/workstation";
(7) "Totally automatic".

The "Information and control" categories are:

(1) "Totally manual";
(2) "Decision giving";
(3) "Teaching";
(4) "Questioning";
(5) "Supervision";
(6) "Intervene";
(7) "Totally automatic".

Each level of the two categories is well described and should help with assigning LOA to the computerised and mechanised tasks in the production system. The method has been applied, tested and verified in the industry by the author (Frohm 2008). For assessing and measuring LOA, Dynamo method can best be applied at the early developing stages of manufacturing process strategies (Lindström and Winroth 2010), and as a part of proactive approach to assembly systems, which measures LOA on the levels of mechanical and information work tasks (Dencker, Fasth et al. 2009). The proactive approach expands LOA and combines them with a Level of

Information (LOI) and a Level of Competence (LOC), which can increase efficiency, decrease reaction time and reduce disturbances (Dencker, Fasth et al. 2009).

viii. Human-Automation Interaction

Sheridan and Parasuraman (2005) presented 8-level "Scale of degrees of automation", where:

(1) "The computer offers no assistance; the human must do it all"
(2) "The computer suggests alternative ways to do the task"
(3) "The computer selects one way to do the task, and"
(4) "Executes that suggestion if the human approves, or;"
(5) "Allows the human a restricted time to veto before automatic execution, or;"
(6) "Executes the suggestion automatically, then necessarily informs the human, or;"
(7) "Executes that suggestion automatically, then informs human only if asked."
(8) "The computer selects the method, executes the task, and ignores the human."

It is based on the 4-level action stage previously developed by Parasuraman et al. (2000).

ix. Human-Automation Collaboration Taxonomy (HACT)

In 2009, Cummings and Bruni further expanded Parasuraman et al.'s (2000) 10-level LOA model into their own model called "Human-Automation Collaboration Taxonomy (HACT)" (Cummings and Bruni 2009). HACT focuses specifically on decision making, and involves three steps: Data acquisition, Decision making, and Action taking. There are three basic human roles in this model: the moderator (helps with the decision making process, making sure the phases are executed), the generator (generates feasible solutions from the data; also known as the "solution generator"), and the decider (selects and makes the final decision out of the sets of solutions, and can veto over the decision selection). Decision-support systems are categorised across these three different roles and five "degrees of collaboration", as presented in Table 5-2 and Table 5-3 (Cummings and Bruni 2009). Three military interface designs were compared and the solution was presented in a simple table, as seen in Table 5-4 (Cummings and Bruni 2009). HACT model therefore presents the operator-automation levels of interaction from the standpoint of a decision-making process between the operator and automation.

Table 5-2 Three different roles of decision-support systems in HACT

Moderator and generator levels	
2	Human
1	Mixed, but more human
0	Equally shared
- 1	Mixed, but more automation
- 2	Automation

Table 5-3 Five "degrees of collaboration" in HACT

Who assumes the role of decider?	
2	Human makes final decision, automation cannot veto
1	Human or automation can make final decision, human can veto, automation cannot veto
0	Human or automation can make final decision, human can veto, automation can veto
- 1	Human or automation can make final decision, human cannot veto, automation can veto
- 2	Automation makes final decision, human cannot veto

Table 5-4 The result of three interfaces compared in HACT

Interface Designs	**HACT (M/G/D)***	**Performance**
Interface #1: Designed to support manual watching of the missiles to the missions at a low level of collaboration	(2/1/2)	Good
Interface #2: designed to offer the human operator the choice to either solve the mission-missile assignment task manually as in interface, or to leverage automation to collaborate with the computer to	(2/0/2)	Good

Interface Designs	**HACT (M/G/D)***	**Performance**
generate solutions		
Interface #3: Graphical interface that allows the operator to only have access to post-solution sensitivity analysis tools	(2/-1/2)	Poor

5.2.4 'Levels of Automation' and 'allocation of functions' in healthcare

Overall, 'Levels of Automation' (LOA) usually describe how the human role interacts with automation. As seen in the cases above, most of the 'LOA' and/or 'allocation of function' models have been mostly applied to military, aviation and manufacturing environments, and very little to healthcare, including the radiotherapy environment.

One of the examples of 'allocation of functions' and 'LOA' in Radiotherapy in Ireland was Fallon's et al. (2010) research using Parasuraman et al.'s (2000) 10-stage LOA model as a basis for the evaluation of the impact of new technologies being introduced to radiotherapy (Fallon, Chadwick et al. 2010). IDEFØ model of the radiotherapy treatment process was a starting point for the analysis, and was previously developed by the same authors. The LOA model was applied to a number of functions based on the IDEFØ analysis, identifying the levels of automation and its trends in the radiotherapy department. The LOA approach taken was based on the assessment of the impact of automation decisions (allocations) on the various staff roles. An overview of three stages of the radiotherapy treatment process was presented, using the LOA model; a totally manual system, the existing paperless system, and a future system, which will potentially have higher degrees of automation (Fallon, Chadwick et al. 2010). The paper indicates in its discussion that more research should be done in applying LOA to the task levels of the radiotherapy system, and that it should be combined with the models of human performance and interaction with automation.

5.3 Methods

5.3.1 A 'Modified Levels of Automation' model for Brachytherapy

An overview of the methods used for the development of the 'Modified Levels of Automation' model for Brachytherapy

Figure 5-1 explains the approach taken for the development and application of the MLOA model for brachytherapy. The rest of the methods section will explain how the MLOA model was developed and applied, to core team member's operations mapped earlier by using the Hierarchical Task Analysis.

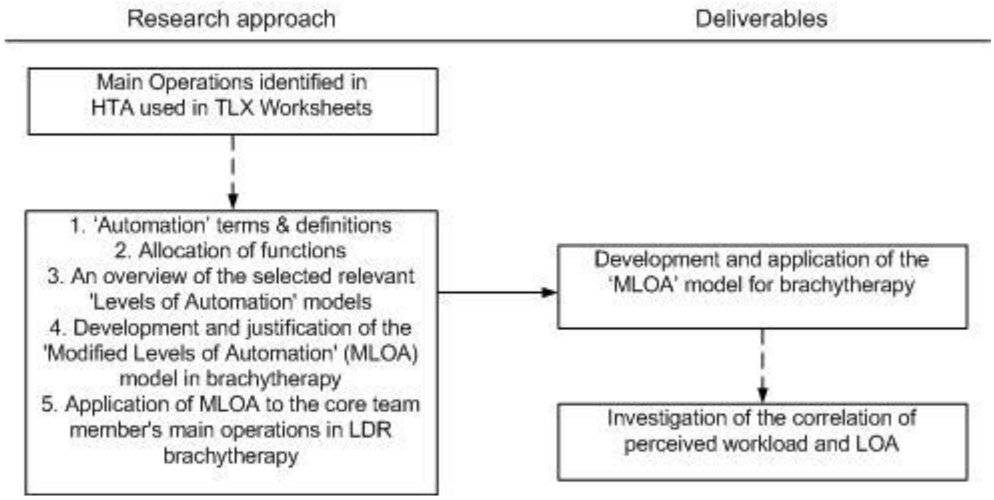


Figure 5-1 Research approach and deliverables of the 'MLOA' model for brachytherapy

Initial development of a 'Modified LOA' model for Radiotherapy / Brachytherapy

The objective of the short conference paper by Galičič et al. (April 2012) was to apply a LOA model to Brachytherapy treatment operations. When trying to apply an appropriate LOA model, a problem arose in terms of which model to apply. None of the mentioned LOA models could be applied directly as they were all missing "something"; they were either too linear, or had decision making stages mixed up with the LOA stages, e.g., a model by Parasuraman et al. (2000), as mentioned in the previous section. This uncovered the need for further development of a 'Modified LOA' model, which could be applicable to the area of radiotherapy, and furthermore, to Low-Dose Rate brachytherapy. Consequently, two LOA models from Parasuraman et al. (2000) and Sheridan (1997) were merged together:

a) The LOA model by Parasuraman et al. (2000) was selected because it featured four action stages and because it featured LOA levels on a graph. However, when LOA were applied, and put in a graph, the average LOA was 5.75, which could be described as "medium" LOA; this was because most of LOA levels had a low LOA, and a few LOA levels had a medium LOA, and so the result was a "medium" LOA.
b) The LOA model by Sheridan (1997), using only two action stages, "Information acquisition and integration", and "Decision and action control" was much easier to apply rather than the four action stages model. If some of the steps were to be applied to the four-stage model, it would sometimes be very difficult to decide which LOA level had to be applied to which stage, as it was unclear to allocate functions between human or machine. The two-stage LOA model simplified the application.

However, a 'Modified Levels of Automation (LOA)' model was not developed to the final stage, and it remained unclear if two, or a four-stage "action" stages should be used. A few questions still remained unanswered in the paper by Galičič et al. (April 2012), e.g. What should we (not) automate?, What LOA should the operations have?, What will be the impact of the LOA in the future?

Further development of the 'Modified LOA model' for Low-Dose Rate brachytherapy

This section answers the second research question in this thesis: How can 'Modified levels of Automation' be applied to Low-Dose Rate prostate brachytherapy?

Besides choosing between the two-stage or four-stage model, the LOA definitions of the 10 categories by (Parasuraman, Sheridan et al. 2000) were not entirely suitable for the LDR brachytherapy (or even more generally speaking, Radiotherapy) LOA model. Besides rewritten definitions of a few LOA categories, additional subcategories were added to the existing LOA category definitions to fit the new model. The following steps were taken in the further development of the ‘Modified LOA’ model that would also answer the second research question:

i. Step 1: Defining the steps

Parasuraman et al. (2000) 10-stage LOA model only provided a description for the “Decision making” action stage, and not for three other action stages: “Information acquisition”, “Information analysis”, and “Action implementation”. The LOA levels were slightly rewritten to fit the function allocation application to radiotherapy/brachytherapy.

ii. Step 2: Creation of the sub-level

The main issue with the LOA levels was the highest LOA, 10th LOA, where the computer acts autonomously, without the human input, and therefore takes the human input “out of the loop”. This is why 10th LOA was expanded into two sub-levels: 10a (a new sub-level), and 10b, previously introduced as 10th LOA by Parasuraman et al. (2000). The new sub-level 10a can be described as:

> “The computer decides everything and acts autonomously, ignoring the human: human can veto.”

iii. Step 3: Justification of changes

The justification of changes is outlined in the Discussion section of this thesis. The whole ‘Modified Levels of Automation’ table is presented in Table 5-5.

5.4 Results

5.4.1 A 'Modified Levels of Automation' model for brachytherapy

The 'Modified Levels of Automation' ('MLOA') model presented in Table 5-5 was developed specifically for the LDR prostate brachytherapy. It was applied to both types of LDR prostate brachytherapy: "Loose seeds" brachytherapy and "Stranded seeds" brachytherapy. As well as LDR prostate brachytherapy, it is also applicable to EBRT radiotherapy and other radiotherapy treatment modalities. An example of the graphical representation of the 'levels of automation' for Radiation oncologist is presented in Figure 5-2. The application of the 'MLOA' model is presented in the next section.

This section answers the following research question descriptively and practically: "How can 'Modified Levels of Automation' be applied to Low-Dose Rate prostate brachytherapy?"

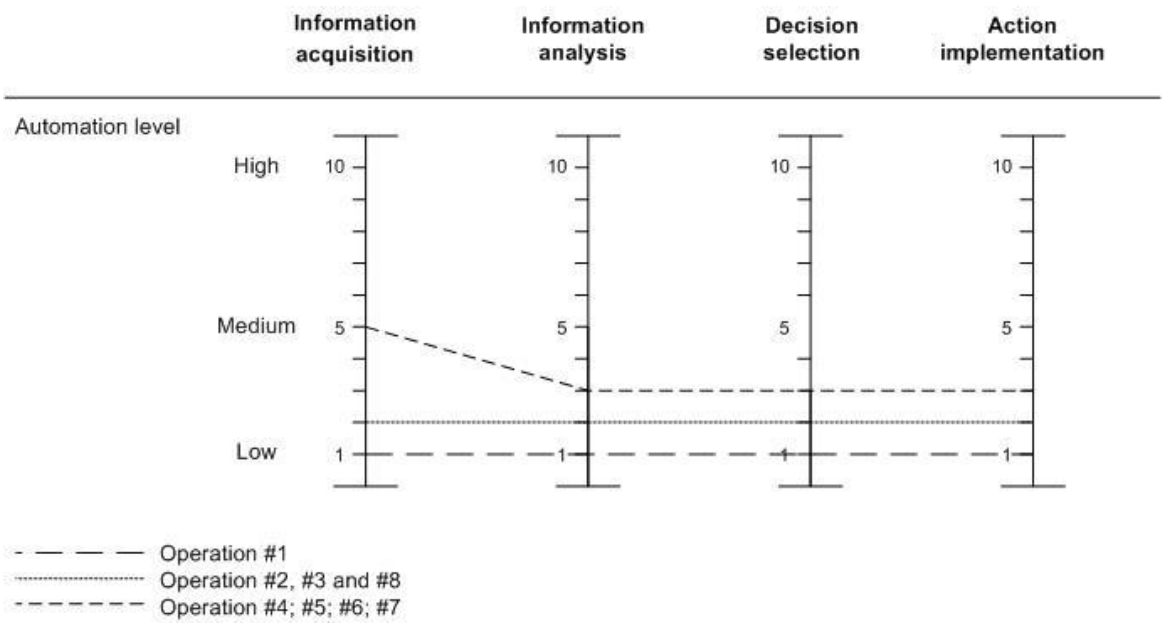


Figure 5-2 A graphical representation of the 'MLOA' for the Radiation oncologist's operations

Table 5-5 A 'Modified LOA model' for brachytherapy

LOA	Information Acquisition	Information Analysis	Decision Selection	Action Implementation
1	Human executes everything, without the computer	Human executes everything, without the computer	The computer offers no assistance: the human must take all decisions and actions	Human executes everything, without computer
2	The computer offers a set of alternatives, human does all cognitive functions	The computer offers a set of alternatives, human does all cognitive functions	The computer offers a complete set of decision/action alternatives, or	The computer offers a complete set of action implementation alternatives, or
3	The computer narrows the selection of the data down to a few, or	The computer narrows the selection down to a few, or	The computer narrows the selection down to a few, or	The computer narrows the selection down to a few, or
4	The computer suggests one alternative	The computer suggests one alternative	The computer suggests one alternative	The computer suggests one alternative
5	The computer detects and registers data if the human approves, or	The computer applies cognitive functions only if the human approves	The computer executes that suggestion if the human approves, or	The computer executes that suggestion if the human approves, or
6	The computer allows the human a restricted time to veto before automatic execution, or	The computer allows the human a restricted time to veto before automatic execution, or	The computer allows the human a restricted time to veto before automatic execution, or	The computer allows the human a restricted time to veto before automatic execution, or
7	The computer detects and registers data automatically, then necessarily informs the human	The computer applies cognitive functions on selected data automatically, then necessarily informs the human	The computer executes automatically, then necessarily informs the human, and	The computer executes functions automatically, then necessarily informs the human, and
8	The computer detects and registers data, informs only if asked	The computer applies cognitive functions only if asked	The computer informs the human only if asked, or	The computer executes functions or choices of actions only if asked, or
9	The computer detects and registers the data only if it is necessary	The computer applies cognitive functions only if it is necessary	The computer informs the human only if it, the computer, decides to	The computer executes functions or choices of actions only if necessary
10a	The computer executes everything, acts autonomously, human can veto at any time	The computer does all cognitive functions, acts autonomously, human can veto at any time	The computer decides everything, acts autonomously, human can veto at any time	The computer executes everything, acts autonomously, human can veto at any time
10b	The computer executes everything, acts autonomously, without the human	The computer does all cognitive functions, acts autonomously, ignoring the human	The computer decides everything, acts autonomously, ignoring the human	The computer executes everything, acts autonomously

5.4.2 Application of the 'Modified Levels of Automation' to Low-Dose Rate brachytherapy

The 'Modified Levels of Automation' was applied to both types of LDR brachytherapy: to "Loose seeds" and "Stranded seeds" prostate brachytherapy. The "loose seeds" brachytherapy technique was used at hospital sites 1, 2, and 3. The "stranded seeds" brachytherapy technique was used at hospital site 4.

i. "Loose seeds" LDR brachytherapy

Radiation oncologist

Table 5-6 Loose seeds LDR brachytherapy: Application of the 'MLOA' model to the Radiation Oncologist's operations

Operation		Modified Level of Automation			
		Information Acquisition	Information Analysis	Decision Selection	Action Implementation
1	TRUS placement	1	1	1	1
2	Measure volume	2	2	2	2
3	Needle implantation	2	2	2	2
4	Volume post needle	5	2	2	2
5	Virtual prostate and urethra positioning	5	2	2	2
6	Peripheral seeding and planning	5	2	2	2
7	Central seeding and planning	5	2	2	2
8	Volume post implant *	2	2	2	2

** Only performed at one hospital site*

Medical physicist #1

Table 5-7 Loose seeds LDR brachytherapy: Application of the 'MLOA' model to Medical physicist #1 operations

Operation		Modified Level of Automation			
		Information Acquisition	Information Analysis	Decision Selection	Action Implementation
1	QA of the source activity	1	1	1	1
2	Measure volume	2	2	2	2
3	Volume post needle	2	2	2	2
4	Peripheral plan verification	5	2	2	2
5	Estimate central needle positioning and seed implantation	5	2	2	2
6	Final verification (dosimetry)	5	2	2	2
7	Room monitoring / contouring – no source left	2	2	2	2

Medical physicist #2

Table 5-8 Loose seeds LDR brachytherapy: Application of the 'MLOA' model to Medical physicist #1 operations

Operation		Modified Level of Automation			
		Information Acquisition	Information Analysis	Decision Selection	Action Implementation
1	QA of the source activity	1	1	1	1
2	Room monitoring / contouring – no source left	2	2	2	2
3	Seeds evaluation form	2	2	1	1

Nurse

Table 5-9 Loose seeds LDR brachytherapy: Application of the 'MLOA' model to the Nurse's operations

Operation		Modified Level of Automation			
		Information Acquisition	Information Analysis	Decision Selection	Action Implementation
1	Patient setup	1	1	1	1
2	Seeding	1	1	1	1

Anaesthetist

Table 5-10 Loose seeds LDR brachytherapy: Application of the 'MLOA' model to the Anaesthetist's operations

Operation		Modified Level of Automation			
		Information Acquisition	Information Analysis	Decision Selection	Action Implementation
1	Patient setup	1	1	1	1
2	Patient monitoring	5	2	2	2

ii. "Stranded seeds" LDR brachytherapy

Radiation oncologist

Table 5-11 Stranded seeds LDR brachytherapy: Application of the 'MLOA' model to the Radiation Oncologist's operations

Operation		Modified Level of Automation			
		Information Acquisition	Information Analysis	Decision Selection	Action Implementation
1	Catheter placement & ultrasound positioning	1	1	1	1
4	Assess plan	2	2	2	2
5	Seed placement	2	2	2	2
7	Assess implant	5	2	2	2

Radiologist

Table 5-12 Stranded seeds LDR brachytherapy: Application of the 'MLOA' model to the Radiologist's operations

Operation		Modified Level of Automation			
		Information Acquisition	Information Analysis	Decision Selection	Action Implementation
2	Refine the position, volume study & image acquisition	1	1	1	1
3	Contouring	2	2	2	2
6	Seed placement	2	2	2	2
7	Assess implant	5	2	2	2

Medical physicist #1

Table 5-13 Stranded seeds LDR brachytherapy: Application of the 'MLOA' model to Medical physicist #1 operations

Operation		Modified Level of Automation			
		Information Acquisition	Information Analysis	Decision Selection	Action Implementation
1	Equipment setup & patient data	1	1	1	1
2	Volume study	2	2	2	2
3	Plan & plan printing	2	2	2	2
5	Real time check	5	2	2	2
6	Seed placement & needle positioning	5	2	2	2
7	Final plan verification (Dosimetry)	5	2	2	2

Medical physicist #2

Table 5-14 Stranded seeds LDR brachytherapy: Application of the 'MLOA' model to Medical physicist #2 operations

Operation		Modified Level of Automation			
		Information Acquisition	Information Analysis	Decision Selection	Action Implementation
4	Prepare the needles, seed calibration & prepare the seeds	1	1	1	1
8	Room monitoring	2	2	1	1

Nurse

Table 5-15 Stranded seeds LDR brachytherapy: Application of the 'MLOA' model to Nurse's operations

Operation		Modified Level of Automation			
		Information Acquisition	Information Analysis	Decision Selection	Action Implementation
1	Patient setup	1	1	1	1
2	Needle loading report	1	1	1	1

Anaesthetist

Table 5-16 Stranded seeds LDR brachytherapy: Application of the 'MLOA' model to Anaesthetist's operations

Operation		Modified Level of Automation			
		Information Acquisition	Information Analysis	Decision Selection	Action Implementation
1	Patient setup	1	1	1	1
2	Patient monitoring	5	2	2	2

5.5 Discussion

5.5.1 The main findings of this chapter

The 'Modified Levels of Automation' was applied to both types of LDR brachytherapy: to "loose seeds" and "stranded seeds" prostate brachytherapy. The highest 'MLOA' level of 5 was amongst Radiation oncologists, Medical physicist #1, and Anaesthetists at "Information acquisition" action stage, whereas the highest 'MLOA' level of 2 was in the other three action stages. The lowest 'MLOA' level of 1 was amongst the Nurses in all four action stages. No high levels of 'MLOA' were applied, e.g. 10a) or 10b). This reflects the current levels of technology and 'levels or automation' used at present, and may, when combined with the TLX scores, provide an interesting starting point for recommendations for further developments of such technology from the user-system perspective.

5.5.2 Application of the 'Modified Levels of Automation' to "Low-Dose Rate" brachytherapy

The main reason of splitting up the 10^{th} LOA was the concern for the autonomy of automation. It directly relates to patient safety in radiotherapy/brachytherapy:

a) Radiotherapy context: The 'level of automation' 10b) would present a high hazard if the human operator had no control over the treatment process. Especially in the case of an emergency, when there would be no option but to shut down the machine. The reasons for shutting down may vary, and could be due to human or machine safety issues, e.g. incorrect positioning of the patient, incorrect dose calculation, incorrect dose application, and wrong organ treated, etc.

   If stage 10a) was implemented, the human operator still has the authority to stop the treatment process by pressing the "stop" button, or just by switching the machine off.

b) Brachytherapy context: Similarly to what is mentioned above, the ‘level of automation’ 10b) would present a risk to patient safety, especially at the “Treatment delivery” stage, where human input is crucial. However, this risk would only be applicable at higher LOA, which would be LOA of the future systems, where the “Treatment delivery” stage was partially or fully-automated. This means, the human role would change from the operator to the supervisor. And in case of an emergency, the partially or fully-automated LOA would need to be switched back to manual operation in order to preserve patient safety because in the case of automation failure, the effect on the “human-machine” system could be catastrophic (Wickens, Li et al. 2010).

   In this case, the 10a) level is an answer to the emergency cases, where the operator would take over the control of the procedure to successfully continue or finish the partially or fully-automated operation. However, in the present system such a high LOA still does not yet exist, because the highest LOA in the present system is 5 at “Information acquisition” stage and 3 at the “Information analysis” stage, “Decision selection” stage and “Action implementation” stage, as seen in Figure 5-2.

The tenth LOA now has a new purpose: the machine can still execute everything autonomously, and a human can “veto” at any time. This enables the human operator to stay in control when the machine is performing treatment at all times by supervising the process. The ‘Modified Levels of Automation’ model can therefore be easily applied to the radiotherapy/brachytherapy environment.

The results have answered the third research question: “How can ‘Modified Levels of Automation’ be applied to Low-Dose Rate prostate brachytherapy?” These results will be used to research the relationship between perceived workload and ‘levels of automation’ and are presented in Chapter 7.

5.5.3 Research limitations of ‘Levels of Automation’ model for LDR prostate brachytherapy

The research limitations related to the development of the ‘Modified levels of automation’ model for LDR prostate brachytherapy included:

- The technology being used was very similar across all four hospital sites, and the variation of the type of the automated equipment was very small. A larger sample of hospital sites may possibly find different types of technology being used.
- The current state of the technology may not be advanced enough to represent a variety of “advanced” semi- or fully-automated equipment. The research was limited to the equipment used in the existing clinical environment, and more advanced semi- or fully-automated equipment was not available to analysis.
- All hospital sites used a similar technological set-up and core team member set-up. This ratio may be different at other hospital sites, and therefore the application of the ‘levels of automation’ would result in larger variety of results.
- The research focussed more on the human-automation issues, and not on the machine reliability and maintainability. The assumption was that all reliability and maintainability tasks were performed out of the “Patient treatment” stage, and that the equipment available at the time of the treatment case was fully functional. Therefore, no major software or hardware performance was noted during the observation. Only minor examples were noted, such as software glitches, cable issues between the TRUS and computer, etc. And based on the observation, these minor examples had more to do with the human-automation issues affecting the human performance, than with the machine reliability and maintainability.

5.5.4 Future work and recommendations to automation and ‘Levels of Automation’ in LDR prostate brachytherapy

Future work and recommendations to automation and ‘Levels of automation’ in LDR prostate brachytherapy:

- The ‘MLOA’ should be applied to every existing and future technology in the radiotherapy domain. Hospitals should be aware that new technology may change a people’s perception, the way of working, performance, and consequently even staffing levels. They should also be aware that the staff may have to expand their skills and upgrade their knowledge just to keep up with the latest technologies. A track record of the applied ‘MLOA’ should be kept together along with staff performance reports.
- The development of the radiotherapy equipment should be gradual in order to match it to human adaptation. This includes the shifting of the ‘MLOA’ action stages from predominantly low automation (at present), to moderately mixed automation (in the near future), and eventually to full automation (in the distant future). This development may, however, introduce new trends on human errors in radiotherapy (Fallon, Galičič et al. 2015).

5.6 Conclusions

This chapter has shown that it is possible to apply an appropriate ‘Levels of automation’ model to Brachytherapy, and more broadly, to Radiotherapy. A specific ‘Modified Levels of Automation’ (MLOA) model was developed by merging two selected ‘levels of automation’ models by Parasuraman, Sheridan, et al. (2000) and Sheridan (1997). The MLOA model was applied to each core team member’s operation in both, “Loose seeds” and “Stranded seeds” LDR prostate brachytherapy. Despite research limitations showing the limitations of applying the MLOA model to the current state of the LDR prostate brachytherapy equipment, the MLOA application identified that most of the core team member’s operations had low LOA, and some medium LOA. Medium LOA was identified at specific operations performed by Radiation oncologists, Radiologists, Medical physicist #1, and

Anaesthetists. On one hand, a further investigation is needed on how the core-team members who are performing these operations interact with the system, that is, to investigate the details of 'human-automation' interaction, and a possible correlation with perceived workload and LOA at these operations. On the other hand, a further investigation is needed on the low LOA and their influence on perceived workload and performance of the core team members.

5.7 Chapter summary

This chapter introduced the topics of automation, 'Levels of Automation' (LOA) and the issues with automation. The main focus of this chapter was to present an overview of nine selected relevant LOA models, and to provide the reasons behind the development of 'Modified Levels of Automation' (MLOA) model for brachytherapy and LDR prostate brachytherapy. An example of MLOA model for brachytherapy was presented, along with the reasons for modification, and research limitations. The MLOA model was applied to the main core team member's operations at LDR prostate brachytherapy identified in previous chapters. The third research question, "How can 'Modified Levels of Automation' be applied to Low-Dose Rate prostate brachytherapy?" was answered. The conclusions highlighted the importance of further investigation of the association between perceived workload and LOA.

Chapter 6: Human-Automation related issues

6.1 Chapter overview

This chapter introduces the topics of automation-related issues, and researches these in a format of a "Human-Automation" questionnaire. The following topics are researched: the user's trust in automation, the user's reliance on automation, the users' reliability/performance, automation-related issues of using brachytherapy equipment, and "Preferred 'Levels of Automation'". The human-automation issues were researched, results presented and discussed. The outcome of the "Human-Automation" questionnaire will be considered in the results summary section of this thesis.

6.2 Introduction

6.2.1 Human-Automation related issues

Four automation related issues were researched in this thesis:

1) The user's trust in automation
2) The user's reliance on automation
3) The users' reliability/performance
4) Preferred 'Levels of Automation'

i. Trust in automation

In Merriam-Webster online dictionary (Merriam-Webster.com 2015), *trust* is defined as:

"Belief that someone or something is reliable, good, honest, effective, etc."

Trust was in relation to automation defined by (Lee and See 2004) as:

"The attitude that an agent will help achieve an individual's goals in a situation

characterised by uncertainty and vulnerability".

General understanding of the word "trust", is in terms of "trusting someone", as in, trusting a person. Trust towards machines, or more generally, "automation" could therefore be described as "trusting something", as in, trusting a machine or "trust in automation" (Muir 1994). Examples of trust in automation can be found in everyday life, e.g. transport (driving a car), time management (using a digital calendar), communication (mobile phones), data storage (internal and external data storage), etc. Although, when trust in humans was compared with trust in automation, the bias was towards automation, as people reacted differently towards automated advice versus human advice (Madhavan and Wiegmann 2004). Furthermore, the authors reported that the users of automation benefit more if automation incorporates human characteristics, e.g. behavioural actions, voice alert, etc. (Madhavan and Wiegmann 2004).

Trust is one of the major factors when interacting with automation (Lee and See 2004), who performed a study where the participants were screening luggage for guns on the X-ray screening machine in a simulated environment. The authors concluded that different trust constructs exist, and that individuals with higher initial trust and higher prosperity to trust machines are more likely to expect the machine to perform correctly. They also concluded that the user's perception of automation play a vital role in trust in automation, and is history based (Lee and See 2004).

Montague et al. (2010) researched trust in medical technology, that is, trust between the patients and medical technology. Their focus was therefore not on trust between the medical personnel and technology, but on trust between the patients and the technology. They, however, presented important constructs on measuring trust that was useful for the development of the "Human-Automation" questionnaire in this thesis. In another paper, Motague et al. (2010) compare the levels of trust in healthcare to aviation industry, and report that different levels of trust have to be present: trust in yourself (e.g. confidence, sufficient experience, abilities, etc.), trusting others (e.g. patient – physician trust), and trust in automation. They also emphasise that other factors are also important for trust in technologies to occur, e.g. successful interaction, accuracy, usability, reliability, consistency, training, enough useful information on how to use the technologies, and options to provide feedback (Montague, Winchester III et al. 2010).

ii. Reliance on automation

In Merriam-Webster online dictionary (Merriam-Webster.com 2015), *reliance* is defined as:

"The state of needing someone or something for help, support, etc"

The users are relying on automation when it provides them with feedback, e.g. display. The automated feedback therefore influences their decision making (Wang, Jamieson et al. 2008) and task success (Beck, McKinney et al. 2009). Human operators can either over- or under- rely on automation (Parasuraman and Riley 1997). According to (Lee 2008; Beck, McKinney et al. 2009) this can lead to:

- Disuse of automation, where the task with a low LOA could be performed with a higher LOA; human operators fail to engage with automation; or
- Misuse of automation, where the task with a high LOA could be performed with a lower LOA; human operators rely on automation when it performs poorly.

Beck et al. (2009) concluded decreased disuse with high personal investment in unaided performance and decreased misuse with high personal investment. "Disuse" of automation means the use of automation at low or manual LOA instead of higher LOA. "Misuse" of automation means over-reliance on higher LOA rather than using low or manual LOA (Parasuraman and Riley 1997). Moreover, Lee (2008) wrote that trust is an important factor in automation, and that disuse has to do with under-trust, while misuse with over-trust. With high workload, misuse is more likely to occur than disuse. The author concluded that it is important that human operators co-evolute and adapt to automation (Lee 2008).

iii. Reliability/performance

In Merriam-Webster online dictionary (Merriam-Webster.com 2015), *reliability* is defined as:

"1. The quality or state of being reliable
2. The extent to which an experiment, test, or measuring procedure yields the same results on repeated trials"

Moreover, *performance* is defined in (Merriam-Webster.com 2015) as:

"The act of doing a job, an activity, etc"

Automation is expected to be reliable, it is expected to "perform well", and especially, to be safe to use. In healthcare, failure to meet these two factors can lead to errors, compromised patient safety, treatment delays, and high costs of insurance and equipment. On one hand, human operators keep relying on automation to complete the process, especially when the LOA are higher, and automation surpasses human capabilities. On the other hand, the automation relies on the human operator's capacities. Better said, it is limited to human capabilities and competence. However, there are still issues related to automation despite meeting strict standards, regulations, quality assurance protocols. These issues are discussed in the previous chapter.

iv. Preferred 'Levels of Automation'

In Merriam-Webster online dictionary (Merriam-Webster.com 2015), the verb "*prefer"* is defined as:

"To like (someone or something) better than someone or something else"

The question of future automation systems with advanced 'Levels of Automation' will be what 'Levels of Automation' will human operators prefer in terms of still being in "control" of the automation. It will not be the human operators that will adapt to automation. It will be the automation that will adapt to the human operator's capabilities. Not all operators will cope with the high LOA, so there may be an option to choose 'preferred LOA'.

An interesting example of 'preferred LOA' was presented by Prof. Rajni Patel who presented an overview of a robotic systems for prostate Brachytherapy, and compared two categories (Patel 2011):

1) Robotic systems with automated needle positioning, but manual insertion and seed implantation, and
2) Robotic systems with automated needle positioning, insertion and seed implantation

He then mentioned that Radiation oncologists prefer the first option over the second option (Patel 2011). The issue of "preferred" LOA was researched together with other issues related to automation in the "Human-Automation" questionnaire in this thesis.

6.3 Methods

6.3.1 "Human-Automation" questionnaire

The purpose of the questionnaire was to examine how users interact with the automation in the present LDR prostate seed brachytherapy. It also assessed automation-related issues, such as trust in automation, automation reliability/performance, and it featured four LOA stages of the "Modified Levels of Automation' to address the 'Preferred LOA' issue that can be applied to the future automated systems.

The following topics were addressed:

- The user's trust in automation: What is the level of trust the user has in automation and its functions and features, user's knowledge of technology, if they are trained enough to trust technology's functions, if they are afraid to use it, if they trust some machines more than others, if they trust older machines more than new machines, etc.

- The user's reliance on automation: If the equipment used is reliable, then how much does the user rely on automation, if the user is able to perform certain operations and sub-operations without the automated equipment, if they can rely on the information displayed to them, if they can rely on the information available to them, etc.
- The user's reliability/performance when interacting with automation and automated equipment in LDR prostate brachytherapy treatment: It addressed the use and failures of technical equipment, such as TRUS, printer, cables; it addressed fear of using some machines/equipment, decision making support when using the machines/equipment, performance satisfaction, equipment reliability in emergency situations, etc.
- Automation-related issues: control, focus, knowledge, features, in terms of partial/fully automated equipment and procedures, the use of brachytherapy equipment, etc.
- Preferred 'Levels of Automation': What levels of automation users prefer at "Information processing", "Information analysis", "Decision making", and "Action execution" action stages.

The questionnaire focussed solely on the Radiotherapy staff, and was not relevant to patients. All contributions to the questionnaire were voluntary. A Consent Form was signed before completion and can be found in the "Human-Automation" questionnaire in the Appendix G.

This section also answered the fourth research question on how will perceived workload relate to the 'Modified Levels of Automation' in the future Low-Dose Rate prostate brachytherapy system.

6.4 Results

6.4.1 'Human-Automation' questionnaire

The "Human-Automation" questionnaire researched the user-automation interaction at LDR prostate brachytherapy treatment. Twenty five questionnaires were distributed among LDR brachytherapy core team members across four hospital sites in Ireland which participated in the research. The questionnaire was administered to the core team which has the most interaction with the technology at the "Treatment delivery" stage of LDR brachytherapy treatment: Radiation oncologists, Radiologists, Medical physics team, including Radiotherapists and Medical physicists. Radiation oncology nurses and Anaesthetists were not included because their interaction with the LDR prostate brachytherapy equipment was minimal, or they interacted with completely different equipment, designed for their own specific use, e.g. anaesthetists using their own machines, e.g. heart rate monitor, oxygen monitor, blood pressure monitor, etc. Eight questionnaires were returned, which gave the response rate of 32%.

The results of the questionnaire are presented in the sections below, and are structured to follow the questionnaire layout. Please note that the word "participants" relates to the research participants who participated in the questionnaire. The "Human-Automation" questionnaire can be found in Appendix G. The SPSS statistical data can be found in Appendix H.

1. Personal background

The results of the first questionnaire section presented below include: team structure, age range, gender, and information on education, training, and experience.

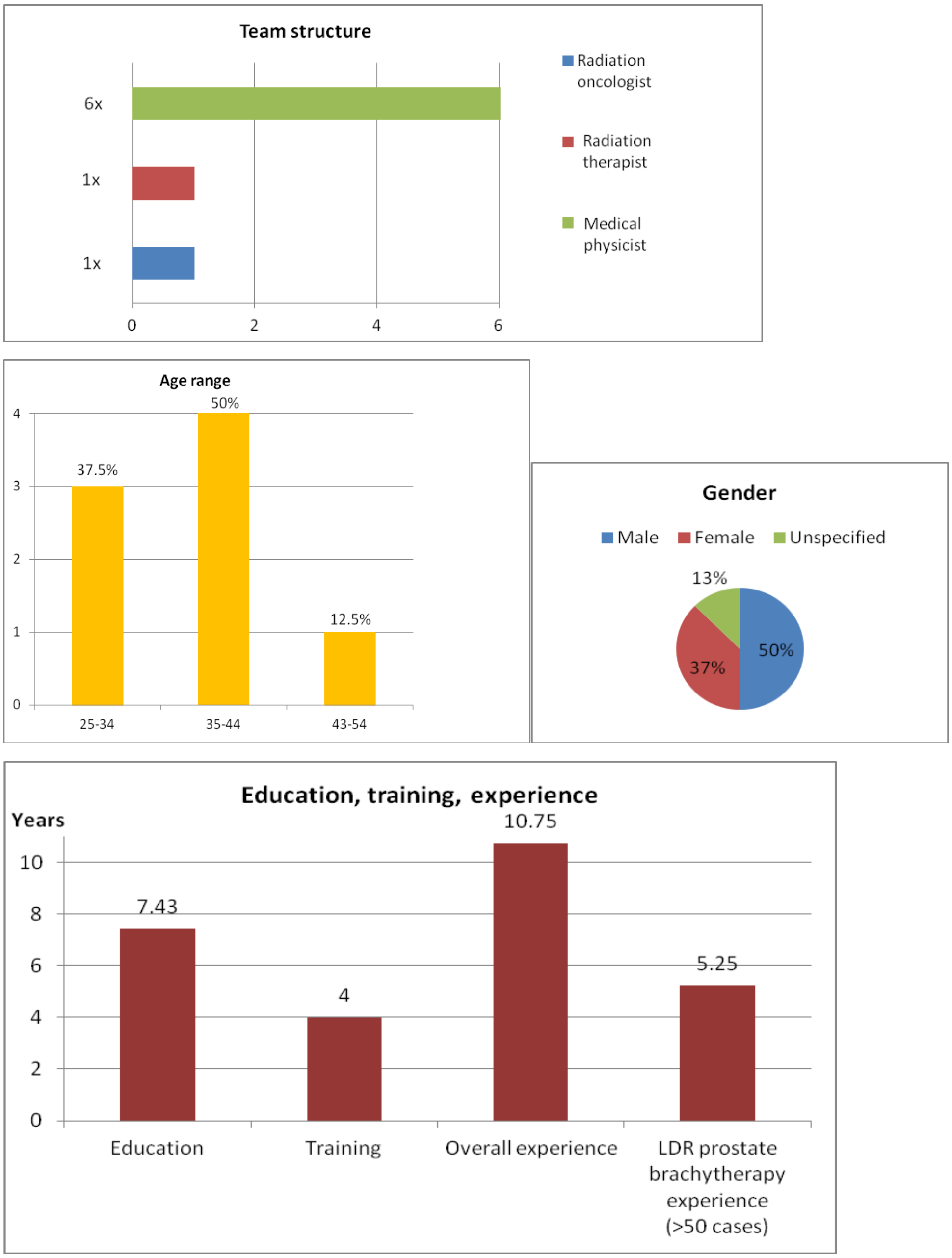


Figure 6-1 Data on personal background

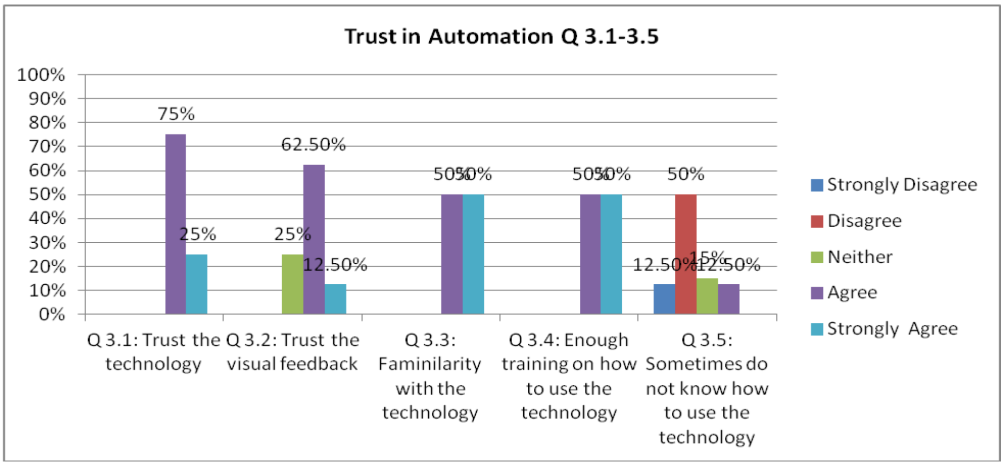
2. Consent form

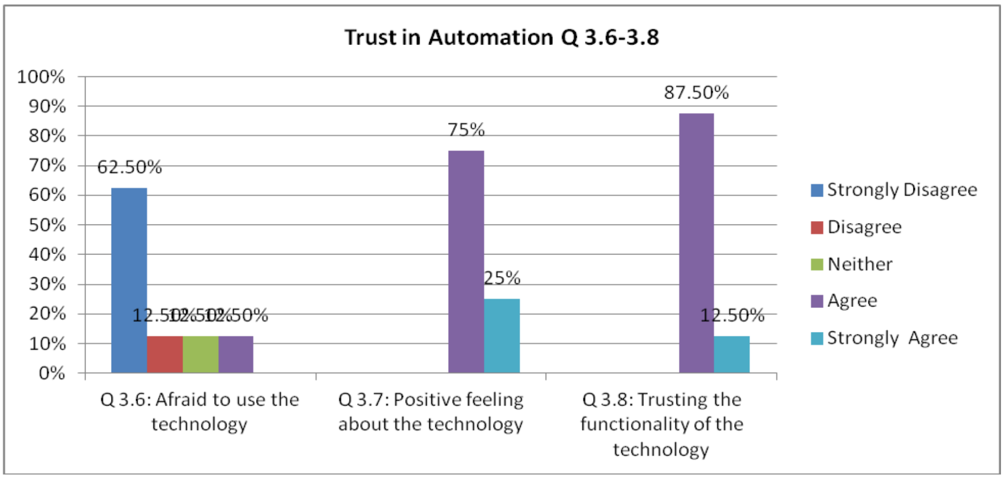
Consent form was signed by all participants.

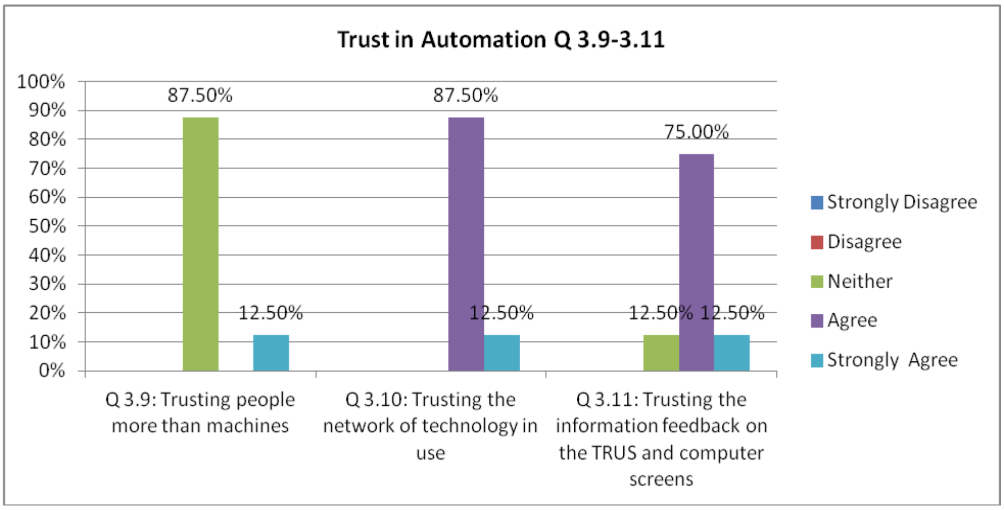
3. Trust in automation

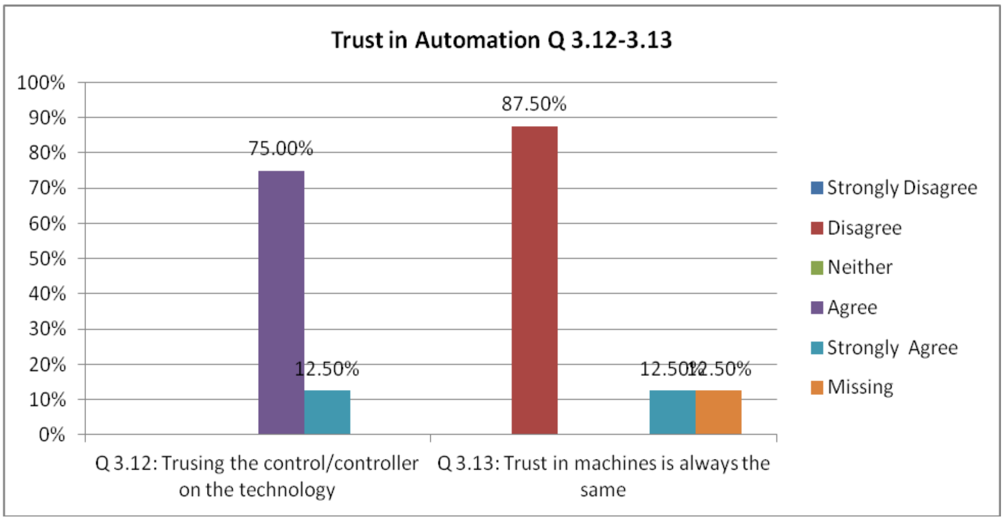
The results of the third questionnaire section are summarised in the figures below. For more details on the questions from the questionnaire refer to

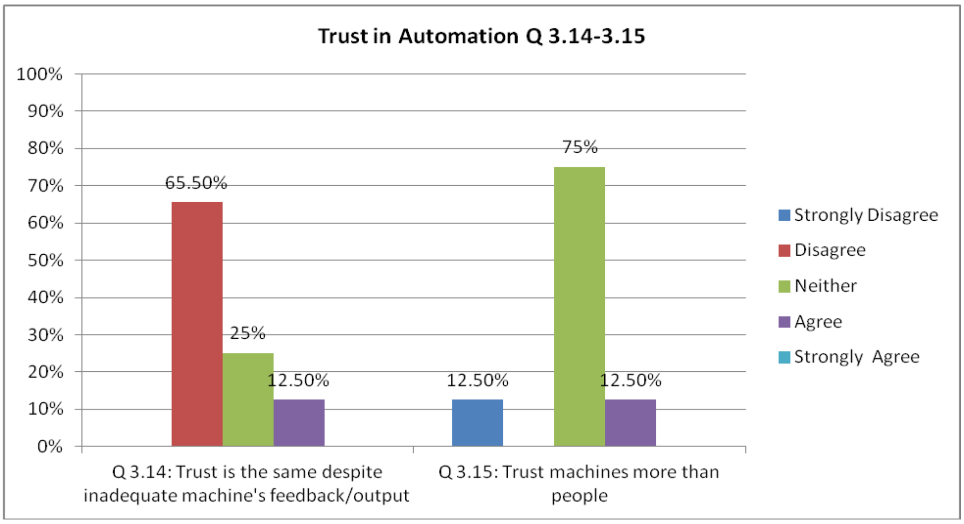
Appendix G. For the statistical data refer to Appendix H.

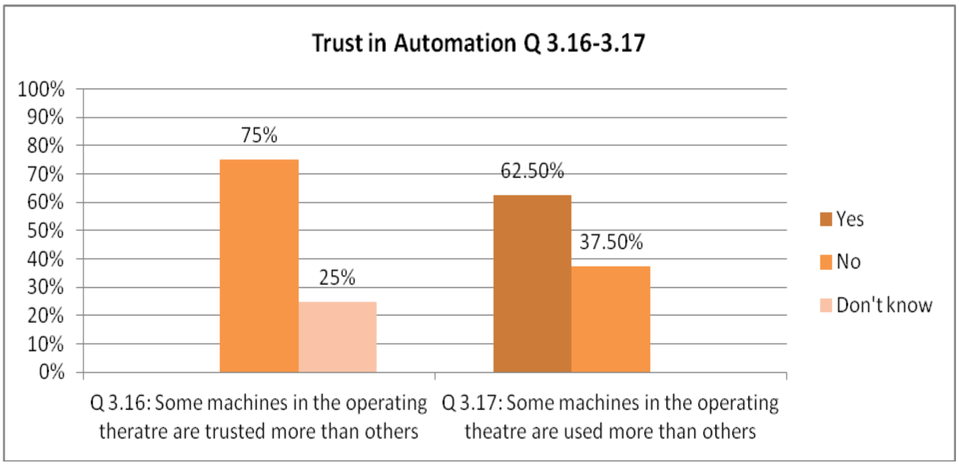


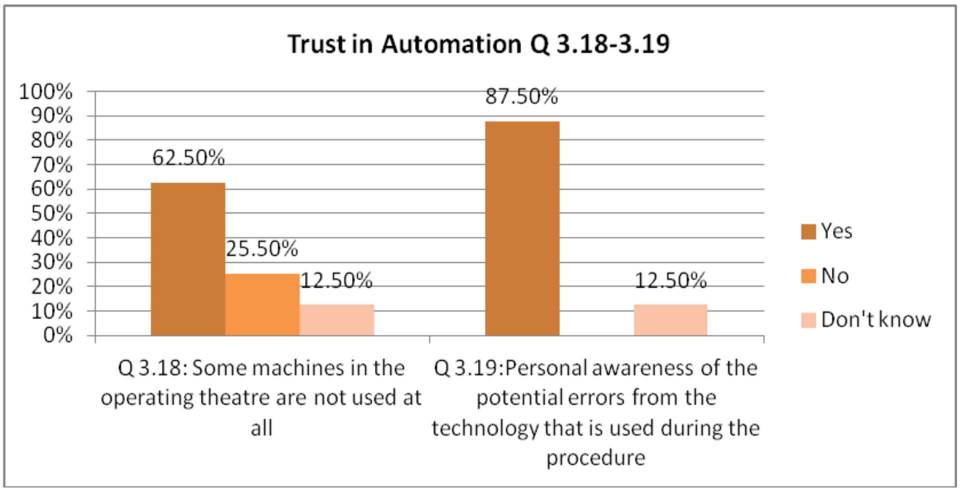





Trust in Automation Q 3.12-3.13
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
75.00%
12.50%
87.50%
12.50%
12.50%
Q 3.12: Trusing the control/controller on the technology
Q 3.13: Trust in machines is always the same
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree
Missing


Trust in Automation Q 3.14-3.15
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
65.50%
25%
12.50%
12.50%
75%
12.50%
Q 3.14: Trust is the same despite inadequate machine's feedback/output
Q 3.15: Trust machines more than people
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree


Trust in Automation Q 3.16-3.17
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
75%
25%
62.50%
37.50%
Q 3.16: Some machines in the operating theratre are trusted more than others
Q 3.17: Some machines in the operating theatre are used more than others
Yes
No
Don't know



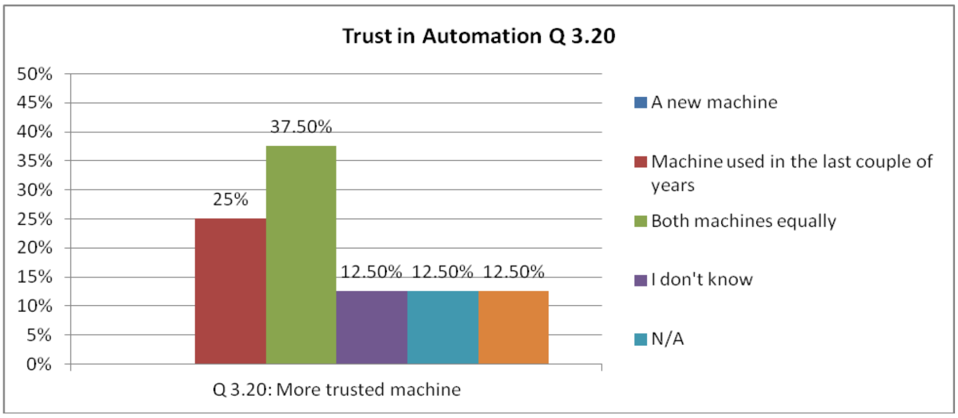
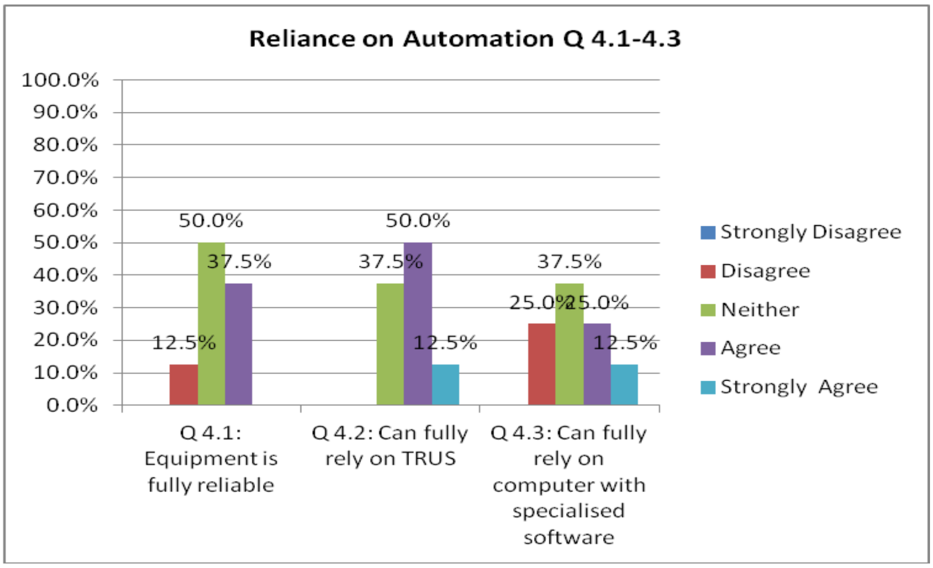
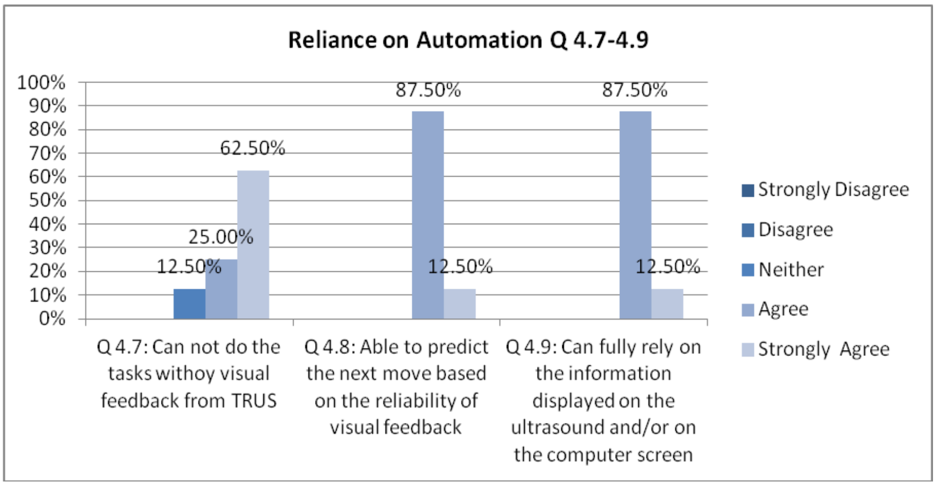


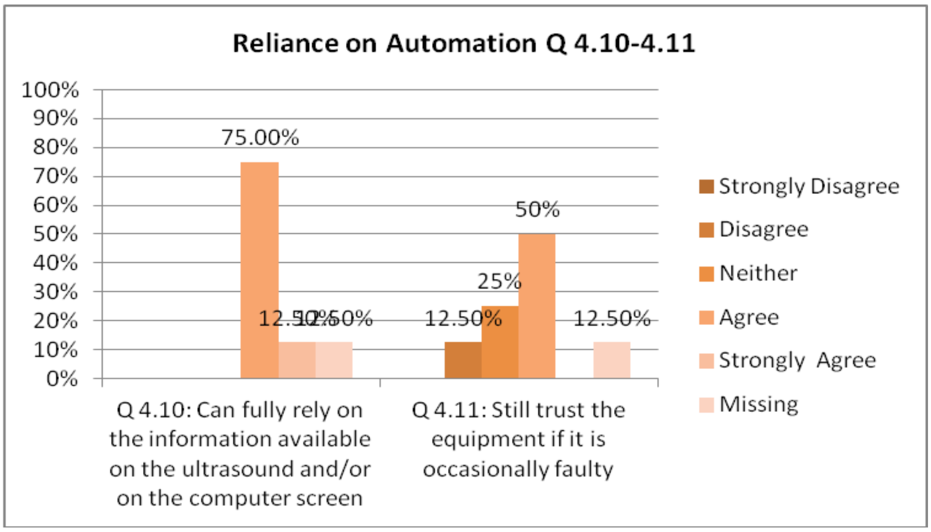
Figure 6-2 Data on trust in automation

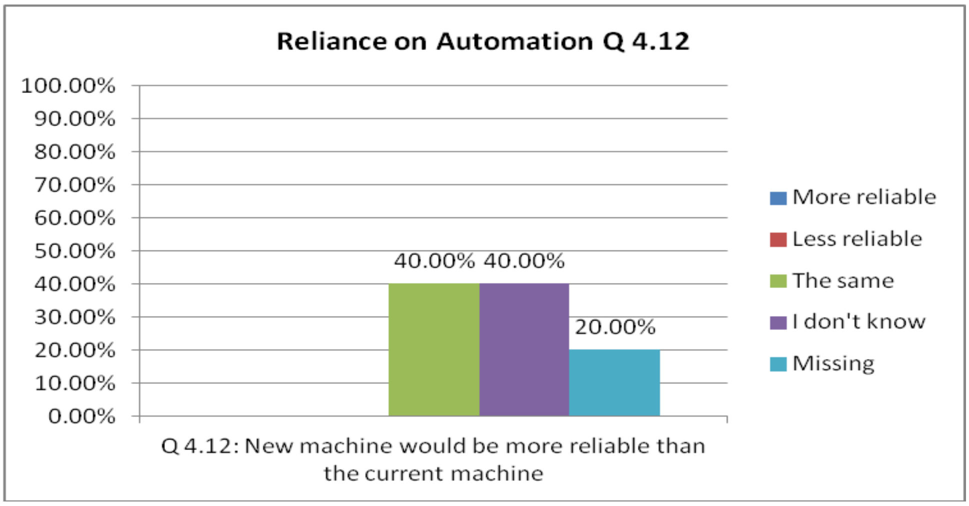
4. Reliance on automation

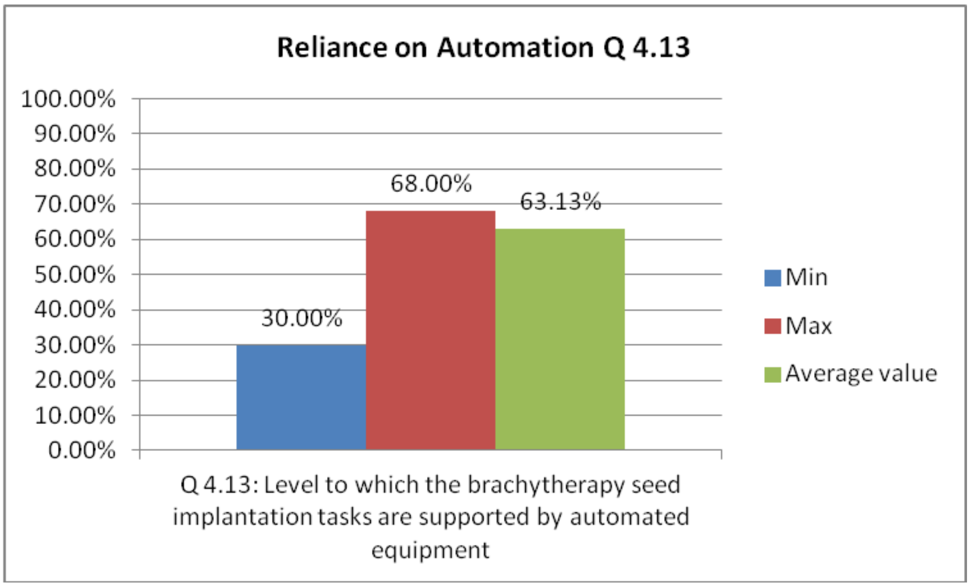
The results of the fourth questionnaire section are summarised in the figures below. For more details on the questions from the questionnaire refer to Appendix G. For the statistical data refer to Appendix H.

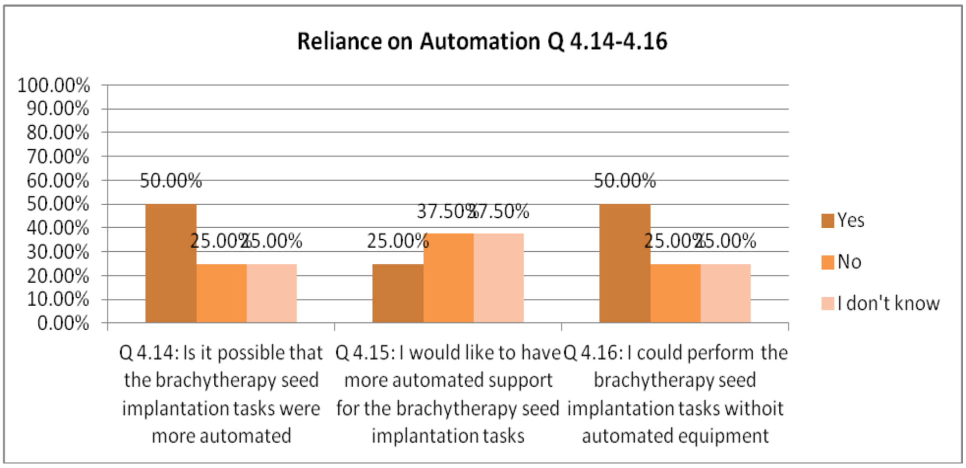

Reliance on Automation Q 4.1-4.3
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
50.0%
37.5%
12.5%
50.0%
37.5%
12.5%
37.5%
25.0%
25.0%
12.5%
Q 4.1: Equipment is fully reliable
Q 4.2: Can fully rely on TRUS
Q 4.3: Can fully rely on computer with specialised software
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree


Reliance on Automation Q 4.7-4.9
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
62.50%
25.00%
12.50%
87.50%
12.50%
87.50%
12.50%
Q 4.7: Can not do the tasks withoy visual feedback from TRUS
Q 4.8: Able to predict the next move based on the reliability of visual feedback
Q 4.9: Can fully rely on the information displayed on the ultrasound and/or on the computer screen
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree


Reliance on Automation Q 4.10-4.11
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
75.00%
12.50%
12.50%
50%
25%
12.50%
12.50%
Q 4.10: Can fully rely on the information available on the ultrasound and/or on the computer screen
Q 4.11: Still trust the equipment if it is occasionally faulty
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree
Missing


Reliance on Automation Q 4.12
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
40.00% 40.00%
20.00%
More reliable
Less reliable
The same
I don't know
Missing
Q 4.12: New machine would be more reliable than the current machine


Reliance on Automation Q 4.13
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
68.00%
63.13%
30.00%
Min
Max
Average value
Q 4.13: Level to which the brachytherapy seed implantation tasks are supported by automated equipment


Reliance on Automation Q 4.14-4.16
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
50.00%
25.00% 25.00%
25.00%
37.50% 37.50%
50.00%
25.00% 25.00%
Yes
No
I don't know
Q 4.14: Is it possible that the brachytherapy seed implantation tasks were more automated
Q 4.15: I would like to have more automated support for the brachytherapy seed implantation tasks
Q 4.16: I could perform the brachytherapy seed implantation tasks withoit automated equipment

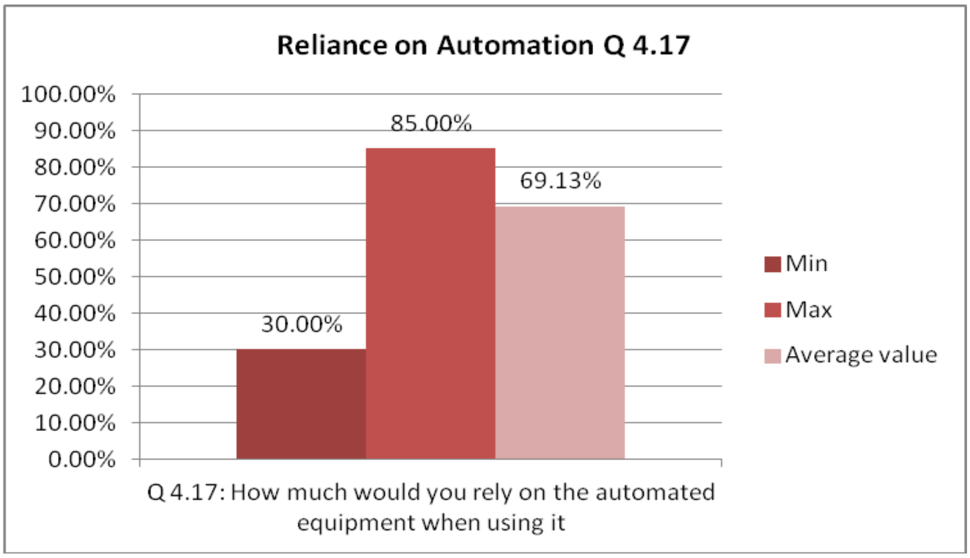
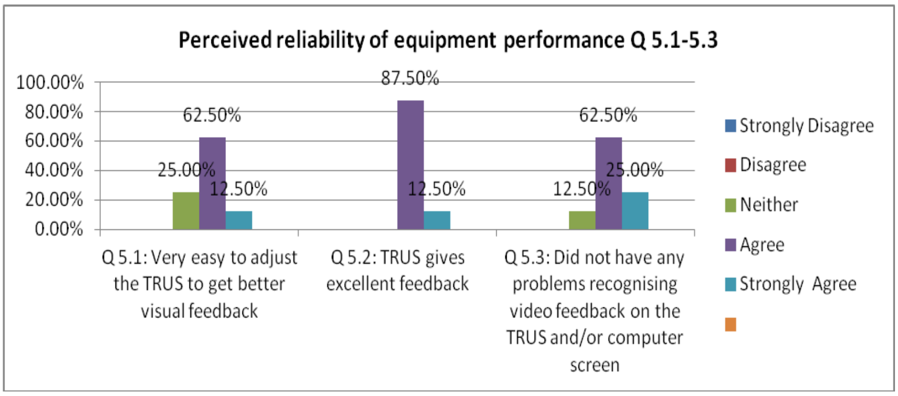
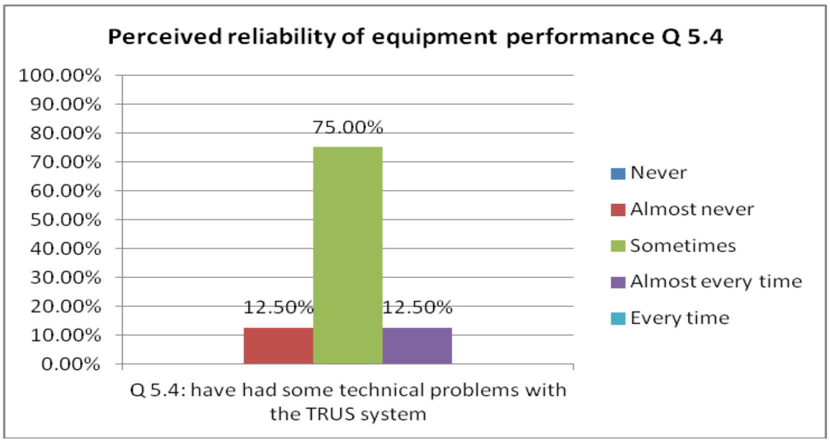


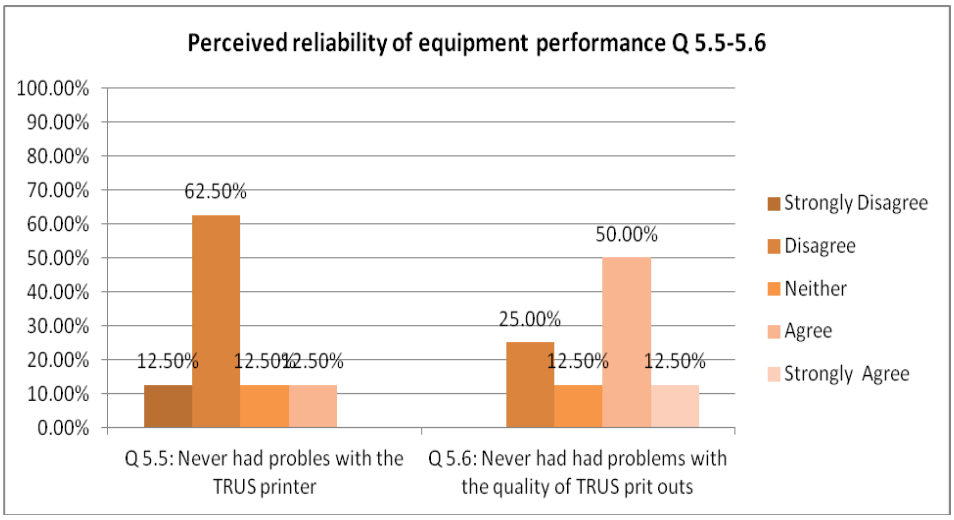
Figure 6-3 Data on reliance on automation

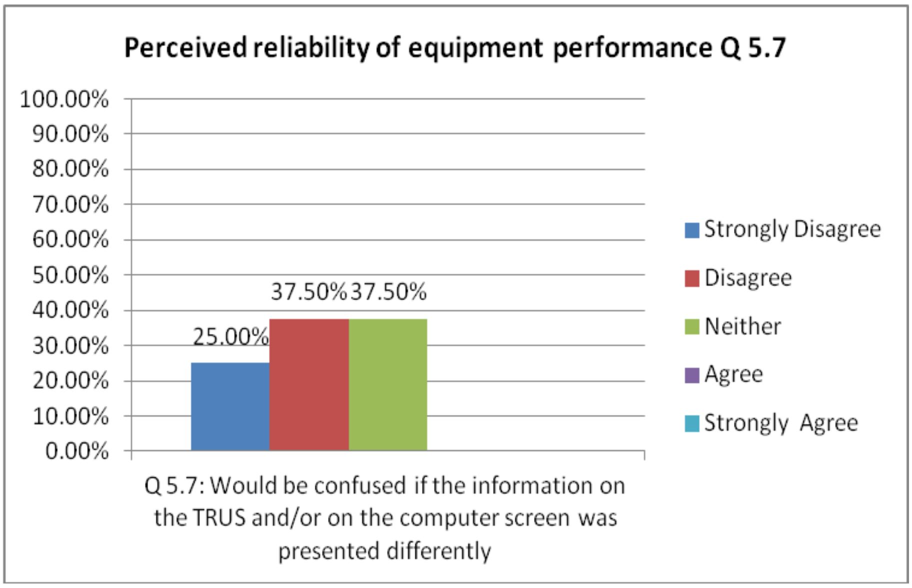
5. Perceived reliability of equipment performance

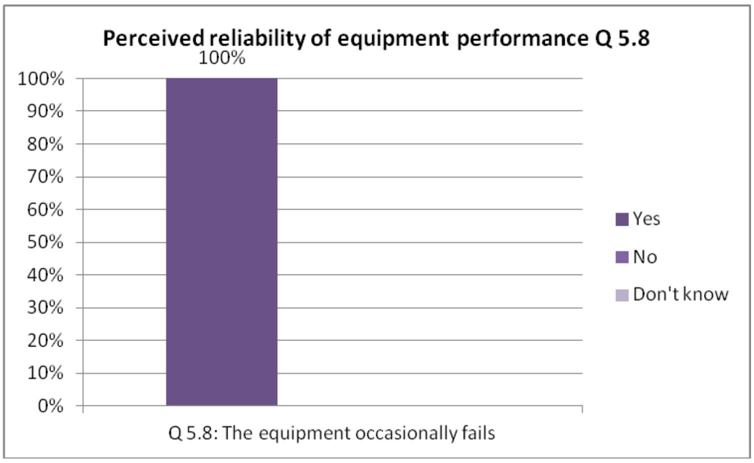
The results of the fifth questionnaire section are summarised in the figures below. For more details on the questions from the questionnaire refer to Appendix G. For the statistical data refer to Appendix H.

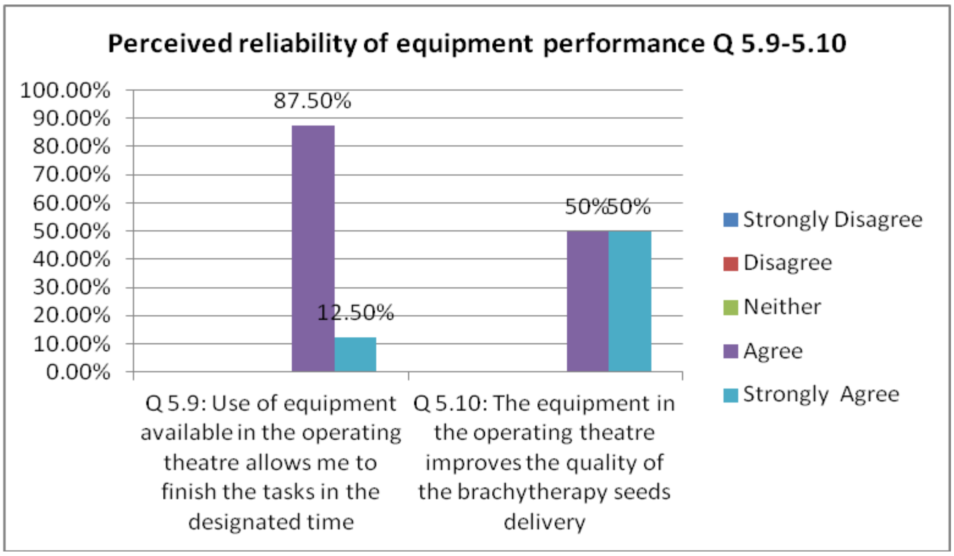


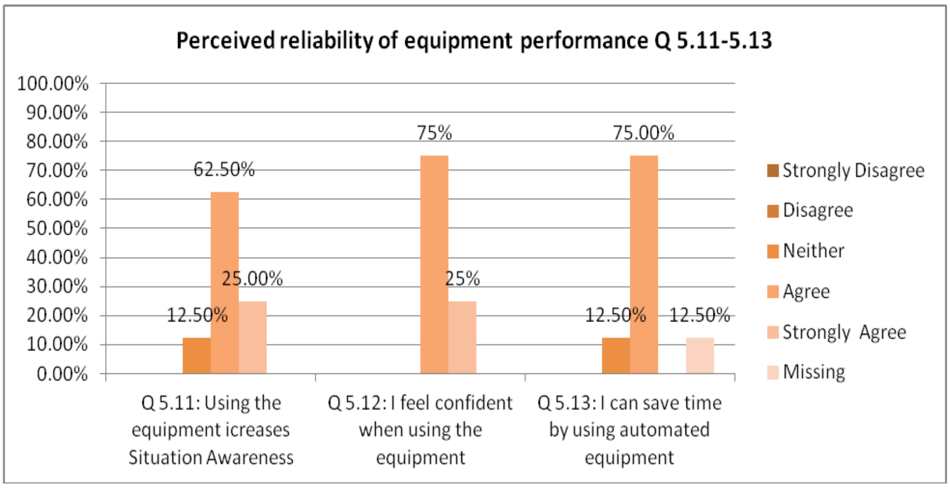

Perceived reliability of equipment performance Q 5.4
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
75.00%
12.50%
12.50%
Never
Almost never
Sometimes
Almost every time
Every time
Q 5.4: have had some technical problems with the TRUS system

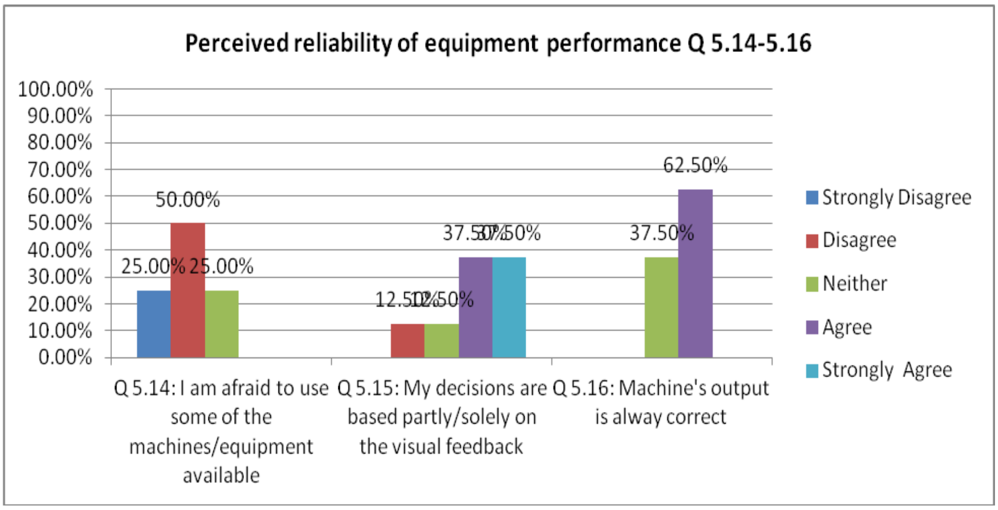

Perceived reliability of equipment performance Q 5.5-5.6
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
62.50%
12.50%
12.50%
12.50%
50.00%
25.00%
12.50%
12.50%
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree
Q 5.5: Never had problems with the TRUS printer
Q 5.6: Never had had problems with the quality of TRUS prit outs

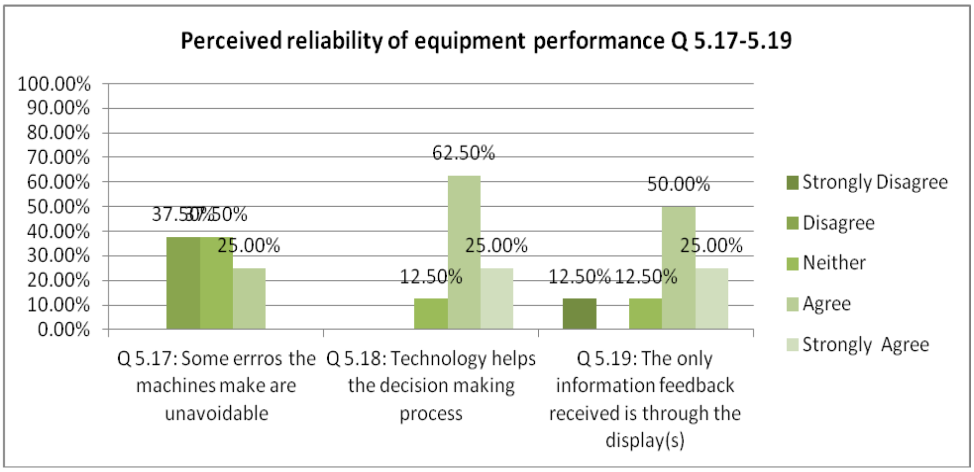

Perceived reliability of equipment performance Q 5.7
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
25.00%
37.50%
37.50%
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree
Q 5.7: Would be confused if the information on the TRUS and/or on the computer screen was presented differently

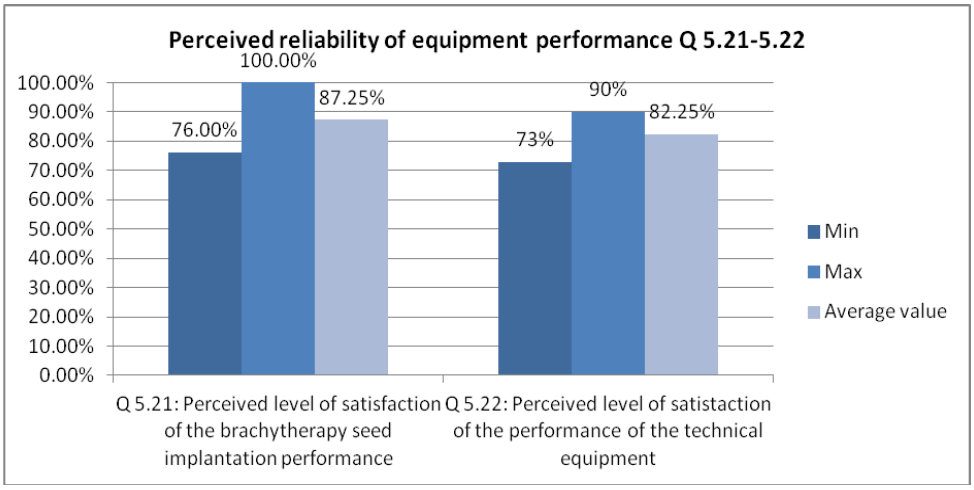

Perceived reliability of equipment performance Q 5.8
100%
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Yes
No
Don't know
Q 5.8: The equipment occasionally fails

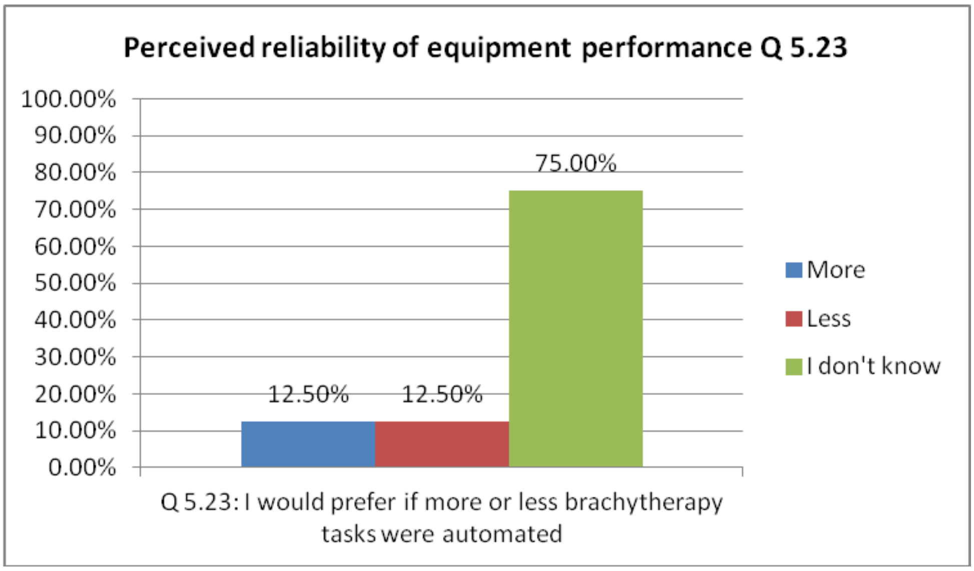

Perceived reliability of equipment performance Q 5.9-5.10
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
87.50%
12.50%
50%
50%
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree
Q 5.9: Use of equipment available in the operating theatre allows me to finish the tasks in the designated time
Q 5.10: The equipment in the operating theatre improves the quality of the brachytherapy seeds delivery

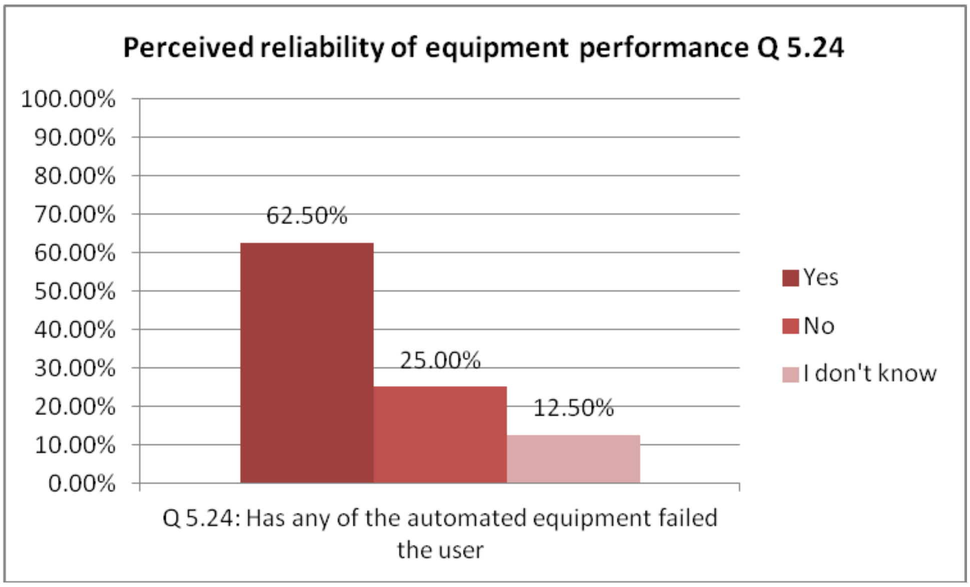

Perceived reliability of equipment performance Q 5.11-5.13
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
62.50%
25.00%
12.50%
75%
25%
75.00%
12.50%
12.50%
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree
Missing
Q 5.11: Using the equipment icreases Situation Awareness
Q 5.12: I feel confident when using the equipment
Q 5.13: I can save time by using automated equipment

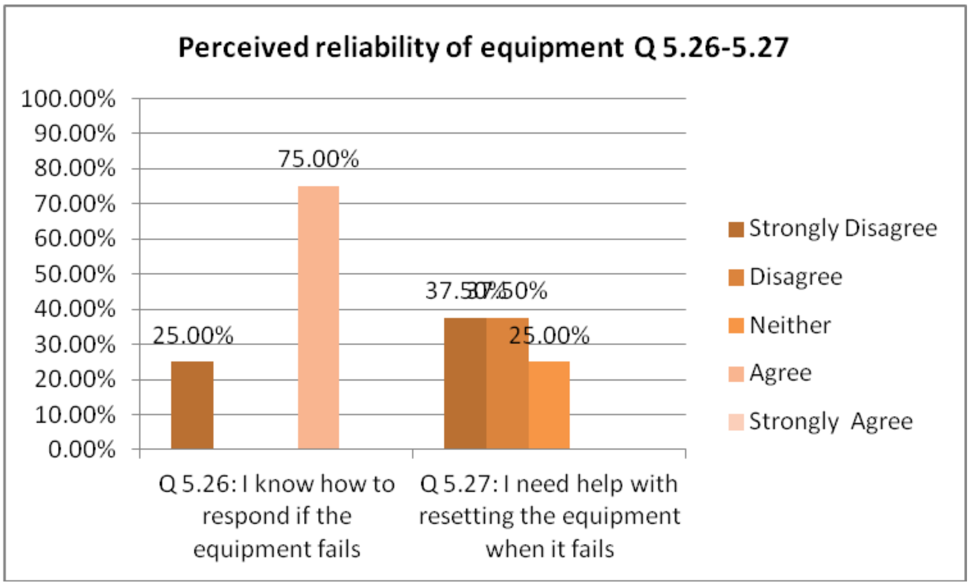

Perceived reliability of equipment performance Q 5.14-5.16
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
50.00%
25.00%
25.00%
12.50%
12.50%
37.50%
37.50%
37.50%
62.50%
Q 5.14: I am afraid to use some of the machines/equipment available
Q 5.15: My decisions are based partly/solely on the visual feedback
Q 5.16: Machine's output is alway correct
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree

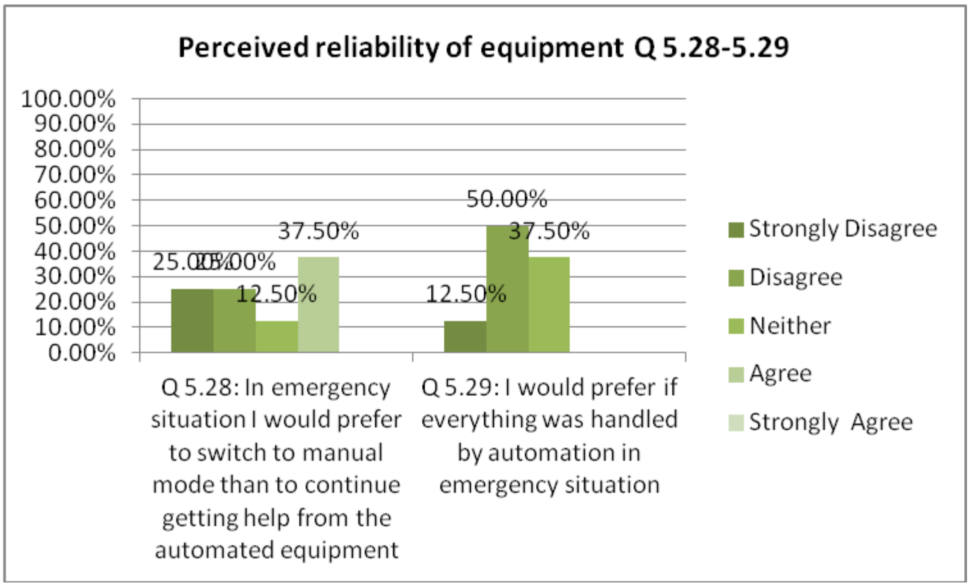

Perceived reliability of equipment performance Q 5.17-5.19
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
37.50%
37.50%
25.00%
62.50%
12.50%
25.00%
50.00%
12.50%
12.50%
25.00%
Q 5.17: Some erros the machines make are unavoidable
Q 5.18: Technology helps the decision making process
Q 5.19: The only information feedback received is through the display(s)
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree

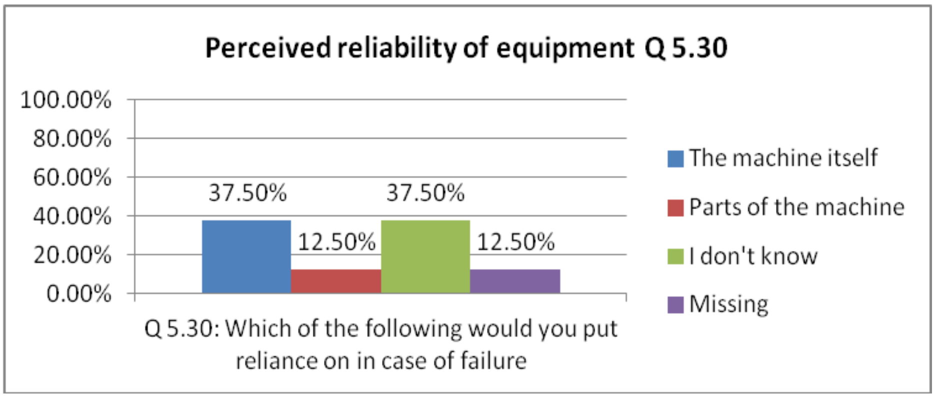

Perceived reliability of equipment performance Q 5.21-5.22
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
76.00%
100.00%
87.25%
73%
90%
82.25%
Q 5.21: Perceived level of satisfaction of the brachytherapy seed implantation performance
Q 5.22: Perceived level of satistaction of the performance of the technical equipment
Min
Max
Average value

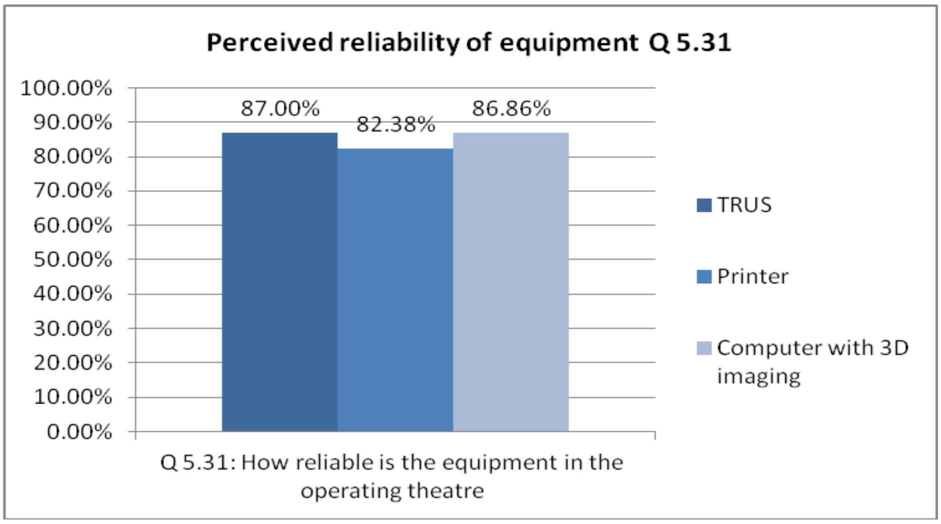

Perceived reliability of equipment performance Q 5.23
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
12.50%
12.50%
75.00%
More
Less
I don't know
Q 5.23: I would prefer if more or less brachytherapy tasks were automated

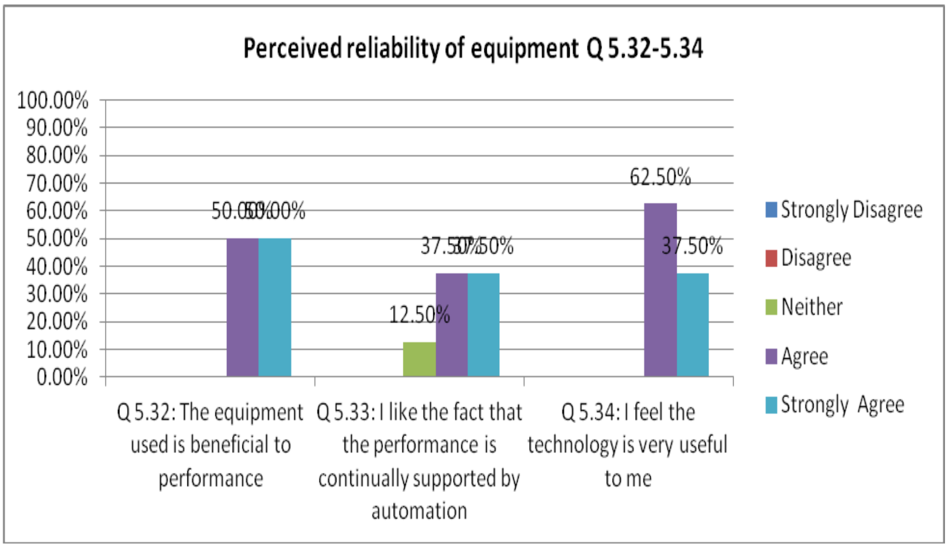

Perceived reliability of equipment performance Q 5.24
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
62.50%
25.00%
12.50%
Yes
No
I don't know
Q 5.24: Has any of the automated equipment failed the user

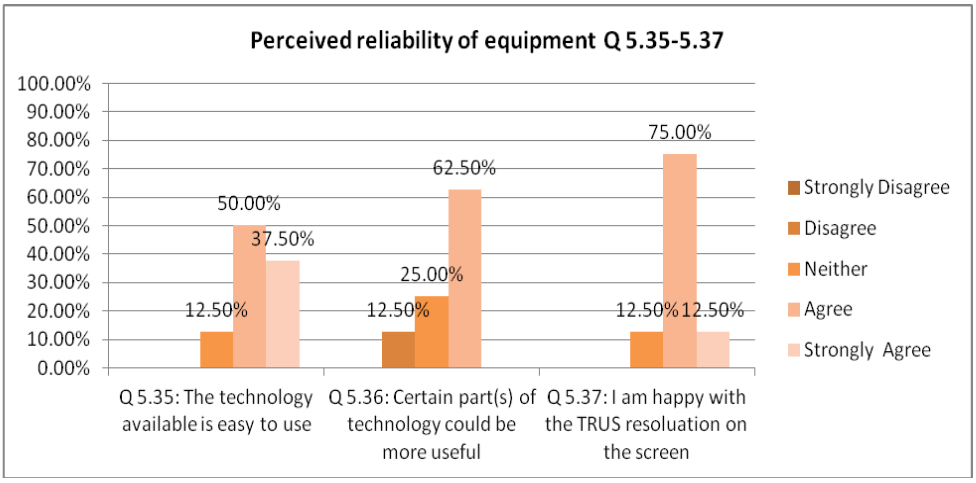

Perceived reliability of equipment Q 5.26-5.27
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
25.00%
75.00%
37.50%
37.50%
25.00%
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree
Q 5.26: I know how to respond if the equipment fails
Q 5.27: I need help with resetting the equipment when it fails

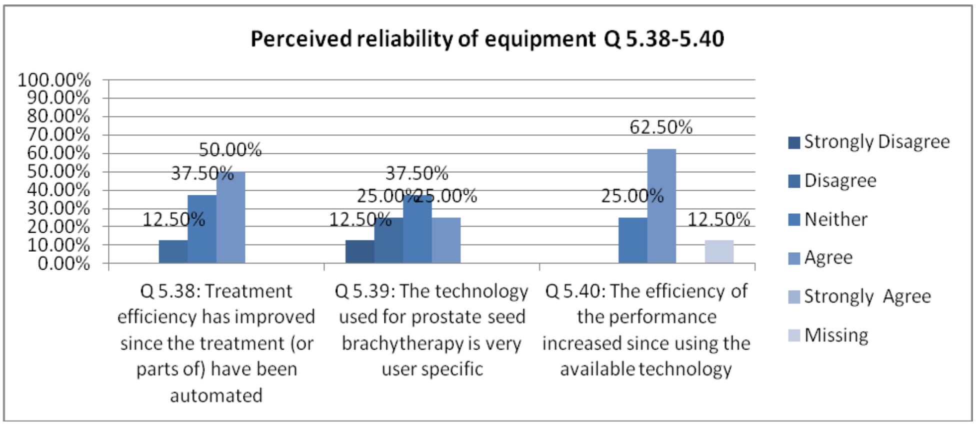

Perceived reliability of equipment Q 5.28-5.29
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
25.00%
25.00%
12.50%
37.50%
12.50%
50.00%
37.50%
Q 5.28: In emergency situation I would prefer to switch to manual mode than to continue getting help from the automated equipment
Q 5.29: I would prefer if everything was handled by automation in emergency situation
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree


Perceived reliability of equipment Q 5.30
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
37.50%
12.50%
37.50%
12.50%
Q 5.30: Which of the following would you put reliance on in case of failure
The machine itself
Parts of the machine
I don't know
Missing


Perceived reliability of equipment Q 5.31
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
87.00%
82.38%
86.86%
Q 5.31: How reliable is the equipment in the operating theatre
TRUS
Printer
Computer with 3D imaging


Perceived reliability of equipment Q 5.32-5.34
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
50.00%
50.00%
37.50%
37.50%
12.50%
62.50%
37.50%
Q 5.32: The equipment used is beneficial to performance
Q 5.33: I like the fact that the performance is continually supported by automation
Q 5.34: I feel the technology is very useful to me
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree


Perceived reliability of equipment Q 5.35-5.37
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
50.00%
37.50%
12.50%
62.50%
25.00%
12.50%
75.00%
12.50%
12.50%
Q 5.35: The technology available is easy to use
Q 5.36: Certain part(s) of technology could be more useful
Q 5.37: I am happy with the TRUS resoluation on the screen
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree


Perceived reliability of equipment Q 5.38-5.40
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
50.00%
37.50%
12.50%
37.50%
25.00%
25.00%
12.50%
62.50%
25.00%
12.50%
Q 5.38: Treatment efficiency has improved since the treatment (or parts of) have been automated
Q 5.39: The technology used for prostate seed brachytherapy is very user specific
Q 5.40: The efficiency of the performance increased since using the available technology
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree
Missing

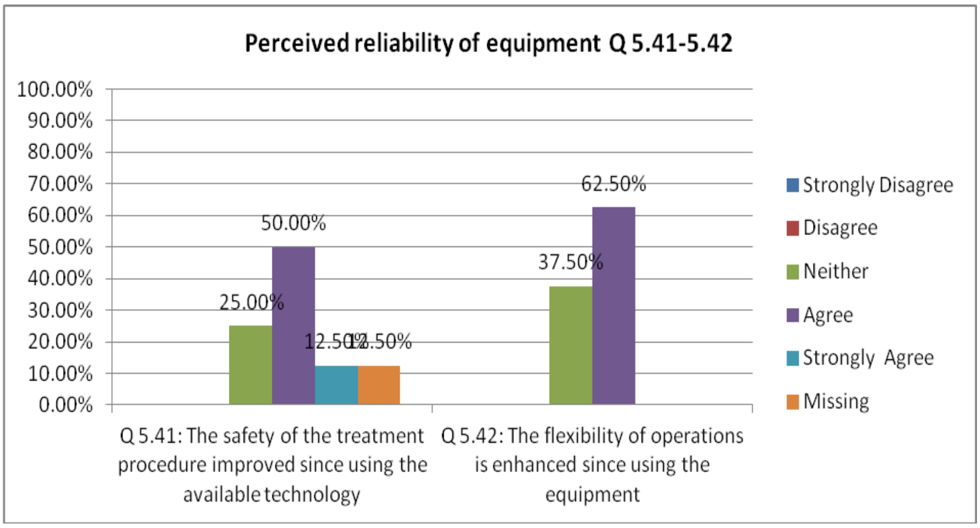
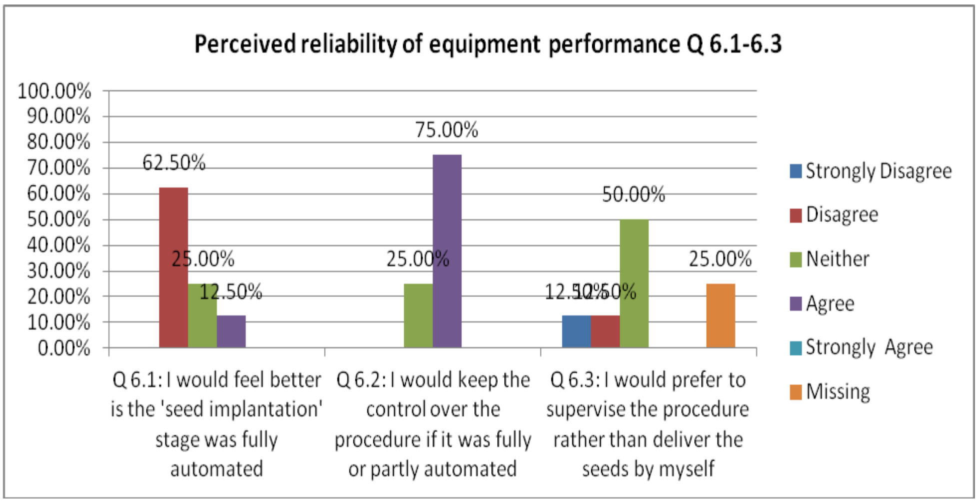
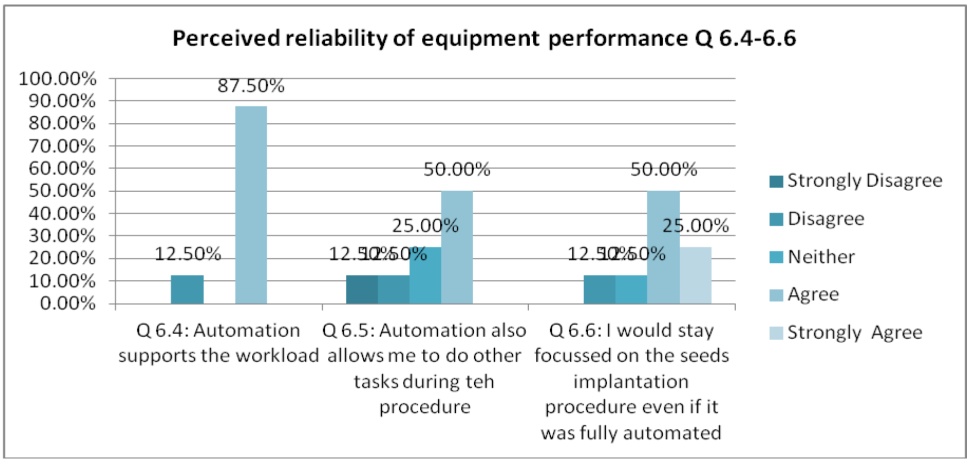


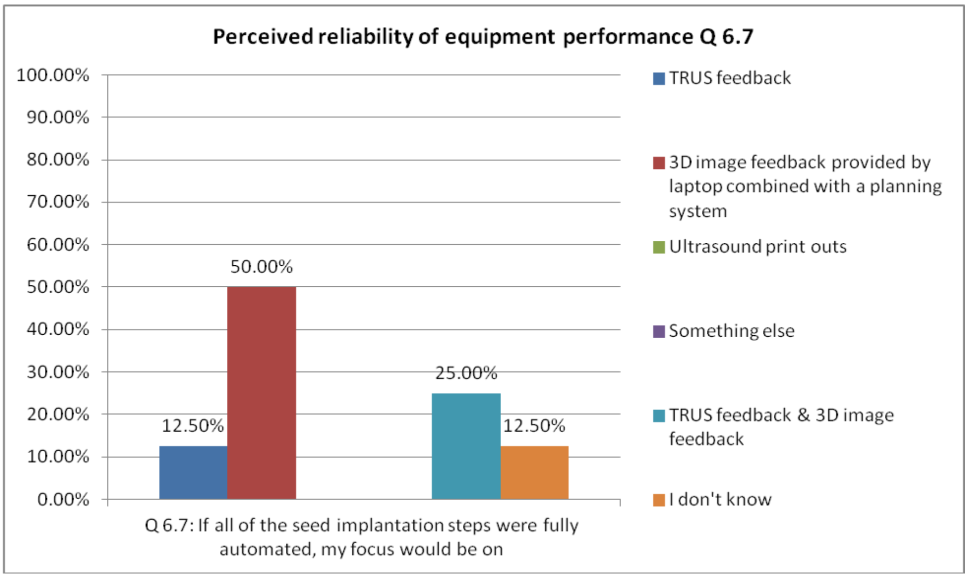
Figure 6-4 Data on perceived reliability of equipment

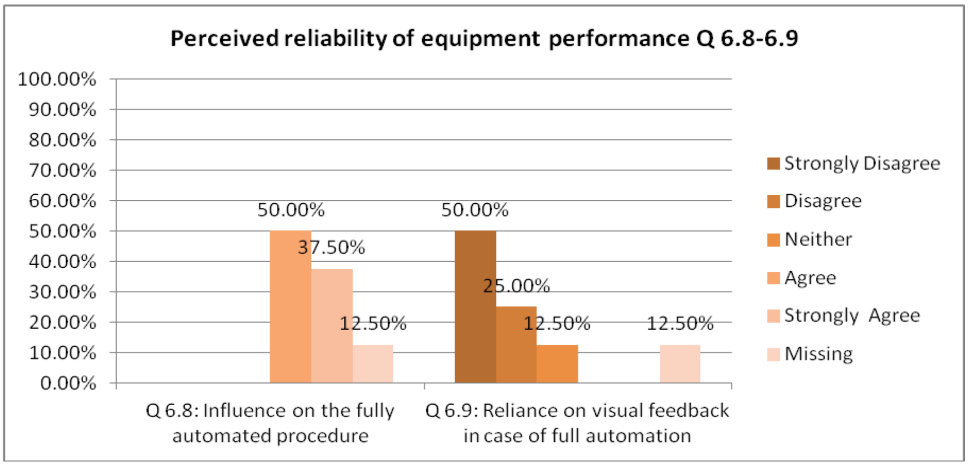
6. Automation-related issues

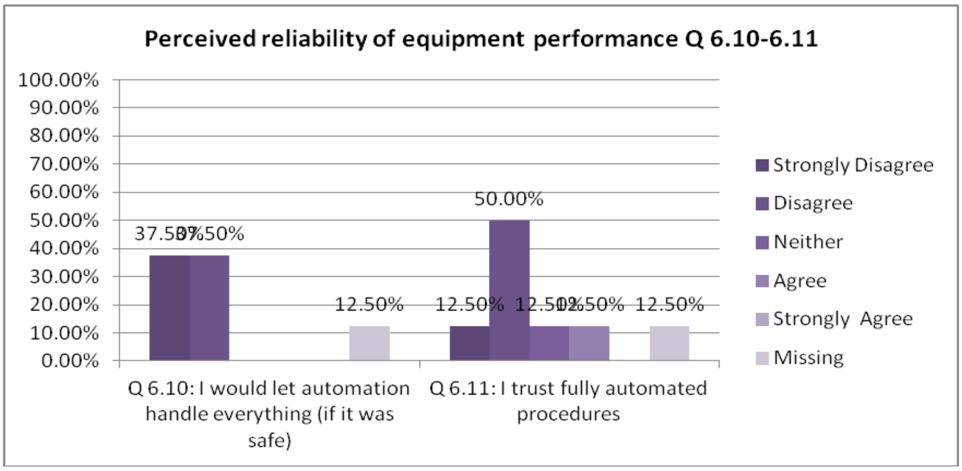
The results of the sixth questionnaire section are summarised in the figures below. For more details on the questions from the questionnaire refer to Appendix G. For the statistical data refer to Appendix H.

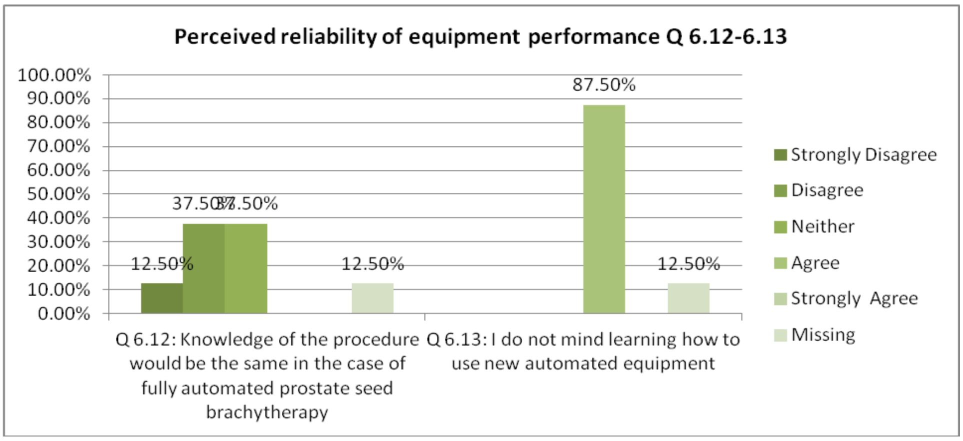


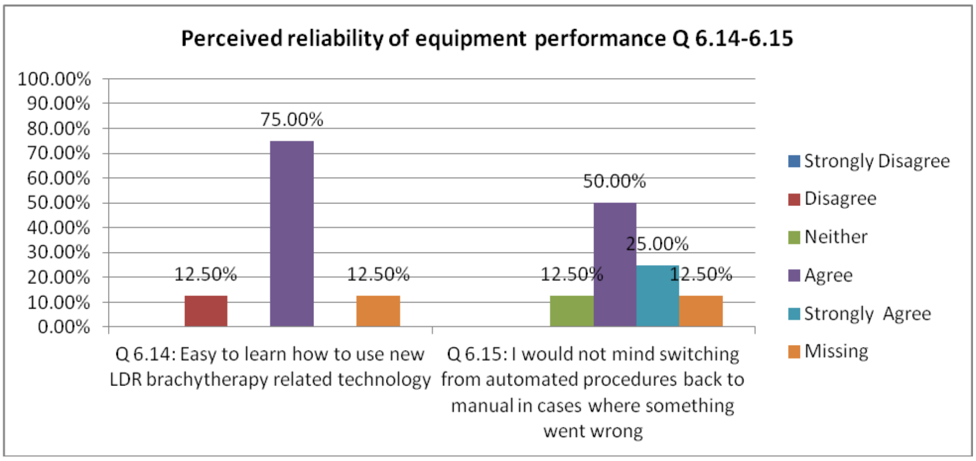

Perceived reliability of equipment performance Q 6.4-6.6
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
87.50%
12.50%
50.00%
25.00%
12.50%
12.50%
50.00%
25.00%
12.50%
12.50%
Q 6.4: Automation supports the workload
Q 6.5: Automation also allows me to do other tasks during teh procedure
Q 6.6: I would stay focussed on the seeds implantation procedure even if it was fully automated
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree

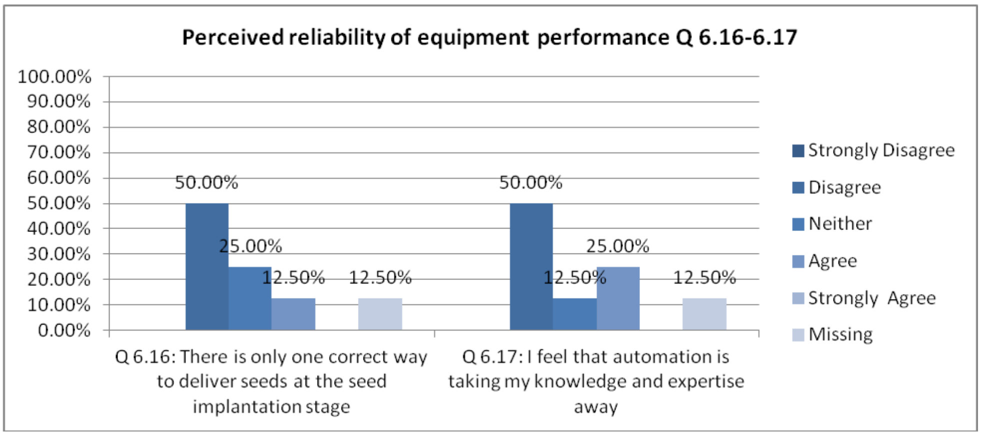

Perceived reliability of equipment performance Q 6.7
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
50.00%
12.50%
25.00%
12.50%
Q 6.7: If all of the seed implantation steps were fully automated, my focus would be on
TRUS feedback
3D image feedback provided by laptop combined with a planning system
Ultrasound print outs
Something else
TRUS feedback & 3D image feedback
I don't know

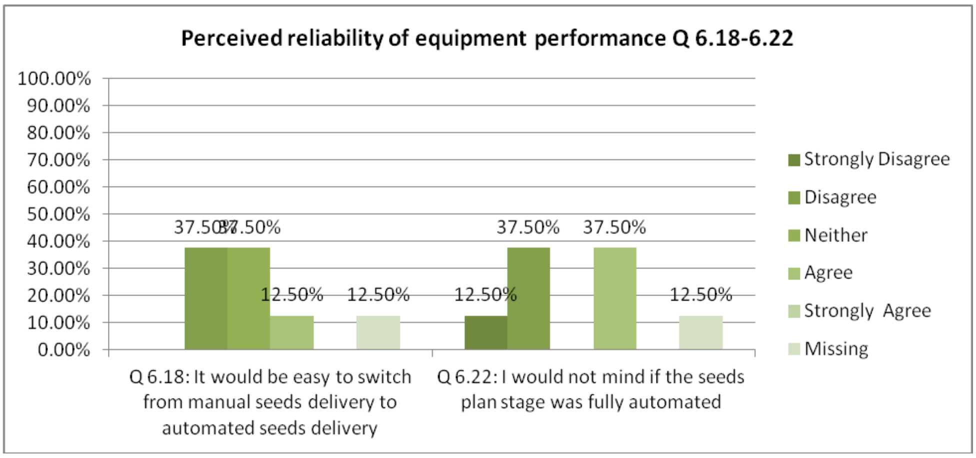

Perceived reliability of equipment performance Q 6.8-6.9
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
50.00%
37.50%
12.50%
50.00%
25.00%
12.50%
12.50%
Q 6.8: Influence on the fully automated procedure
Q 6.9: Reliance on visual feedback in case of full automation
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree
Missing

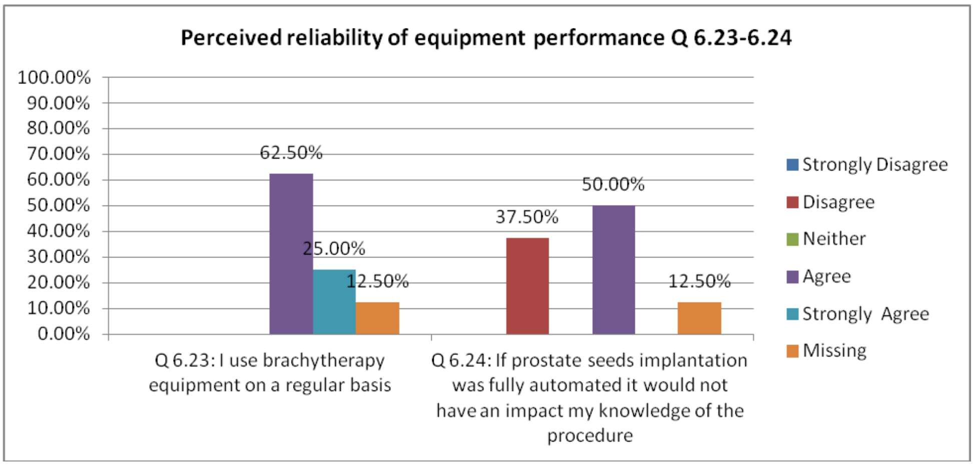

Perceived reliability of equipment performance Q 6.10-6.11
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
37.50%
37.50%
12.50%
50.00%
12.50%
12.50%
12.50%
12.50%
Q 6.10: I would let automation handle everything (if it was safe)
Q 6.11: I trust fully automated procedures
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree
Missing

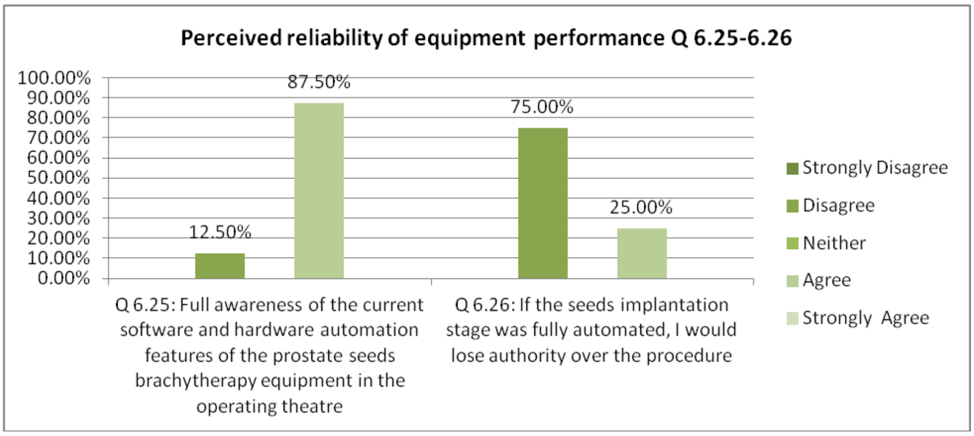

Perceived reliability of equipment performance Q 6.12-6.13
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
12.50%
37.50%
37.50%
12.50%
87.50%
12.50%
Q 6.12: Knowledge of the procedure would be the same in the case of fully automated prostate seed brachytherapy
Q 6.13: I do not mind learning how to use new automated equipment
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree
Missing

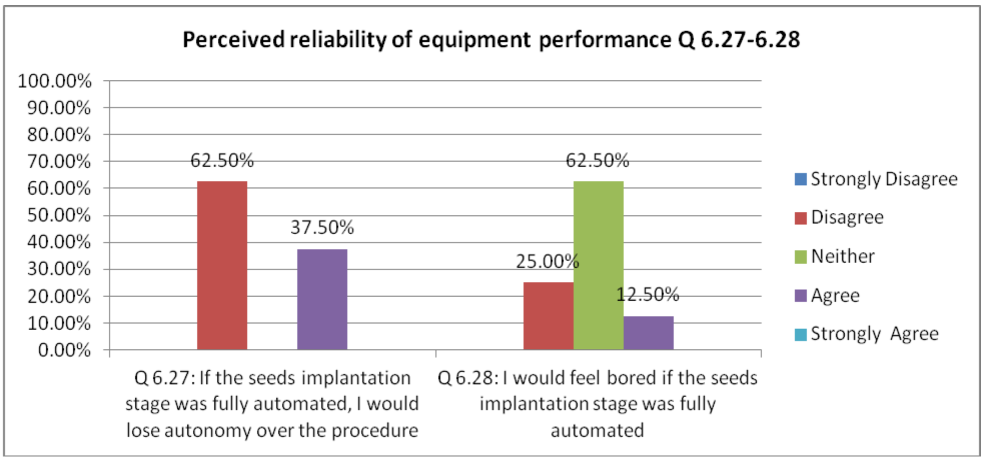

Perceived reliability of equipment performance Q 6.14-6.15
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
12.50%
75.00%
12.50%
12.50%
50.00%
25.00%
12.50%
Q 6.14: Easy to learn how to use new LDR brachytherapy related technology
Q 6.15: I would not mind switching from automated procedures back to manual in cases where something went wrong
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree
Missing

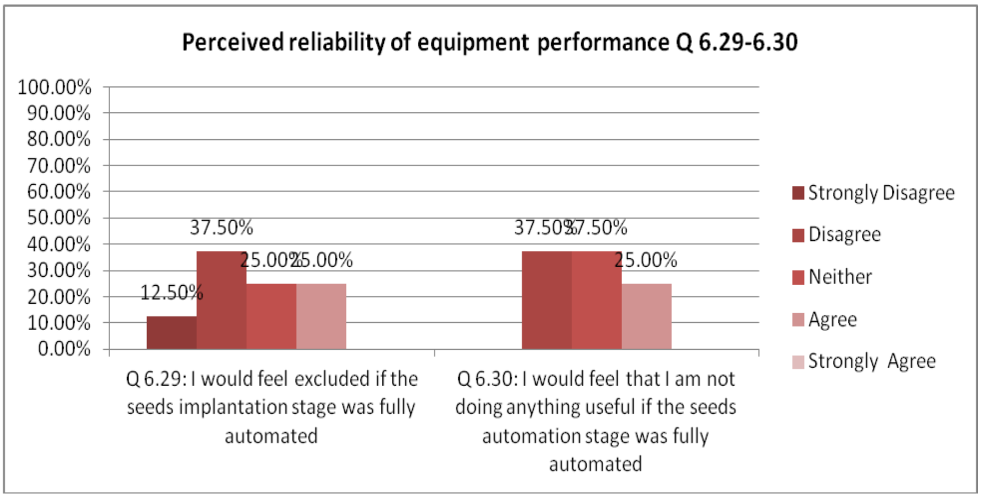

Perceived reliability of equipment performance Q 6.16-6.17
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
50.00%
25.00%
12.50%
12.50%
50.00%
12.50%
25.00%
12.50%
Q 6.16: There is only one correct way to deliver seeds at the seed implantation stage
Q 6.17: I feel that automation is taking my knowledge and expertise away
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree
Missing


Perceived reliability of equipment performance Q 6.18-6.22
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
37.50%
37.50%
12.50%
12.50%
12.50%
37.50%
37.50%
12.50%
Q 6.18: It would be easy to switch from manual seeds delivery to automated seeds delivery
Q 6.22: I would not mind if the seeds plan stage was fully automated
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree
Missing


Perceived reliability of equipment performance Q 6.23-6.24
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
62.50%
25.00%
12.50%
37.50%
50.00%
12.50%
Q 6.23: I use brachytherapy equipment on a regular basis
Q 6.24: If prostate seeds implantation was fully automated it would not have an impact my knowledge of the procedure
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree
Missing


Perceived reliability of equipment performance Q 6.25-6.26
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
12.50%
87.50%
75.00%
25.00%
Q 6.25: Full awareness of the current software and hardware automation features of the prostate seeds brachytherapy equipment in the operating theatre
Q 6.26: If the seeds implantation stage was fully automated, I would lose authority over the procedure
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree


Perceived reliability of equipment performance Q 6.27-6.28
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
62.50%
37.50%
25.00%
62.50%
12.50%
Q 6.27: If the seeds implantation stage was fully automated, I would lose autonomy over the procedure
Q 6.28: I would feel bored if the seeds implantation stage was fully automated
Strongly Disagree
Disagree
Neither
Agree
Strongly Agree



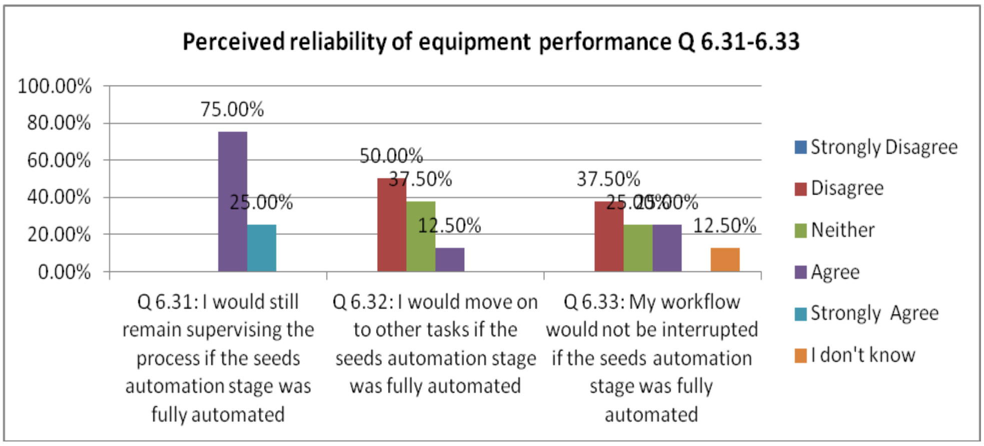


Figure 6-5 Data on perceived reliability of equipment performance

7. Preferred 'Levels of Automation'

The participant would <u>*prefer*</u> if:

7.1 Information sensing was (8) "Shared; the computer would integrate the information into a coherent presentation, with an indication of confidence about each aspect", based on the average mean value of 7.94.

7.2 Information processing was (8) "Shared; the computer would process all information and integrate it into a coherent presentation, with an indication of confidence about each aspect", based on the average mean value of 7.94.

7.3 Decisions were (3) "Shared: the computer narrows the sources down to a few", based on the average mean value of 2.88.

7.4 Actions were (3) “Shared; the computer would narrow the sources of action to a few”, based on the average mean value of 3.38.

7.5 Prostate seeds delivery was (3) “Shared; the computer would narrow the sources of action to a few”, based on the average mean value of 3.25.

6.5 Discussion

6.5.1 The main findings of this chapter

The core team members have a strong trust in technology despite technology being occasionally faulty. They trust the equipment they use, including the TRUS visual feedback, TRUS controller, functionality of the equipment, the technology network, the information presented on TRUS display and/or on the computer display. The trust in information feedback is very strong as well, and this may reflect the high “Information acquisition” LOA action stage. However, the equipment is occasionally faulty, and despite that, the reliance on the automated equipment to complete the tasks was reported as high. The equipment in the operating theatre was reported to be highly reliable and is beneficial to performance, and was assessed as very useful. Though, certain parts of the technology could be more useful. It was reported that the control over the ‘Treatment delivery’ stage would be lost if the “Treatment delivery” stage was fully automated. Although, in such a case, the focus would still be on the ‘Seeds implantation’, in particular on the ‘TRUS’ feedback and ‘3D image feedback’ on the computer, therefore, this implicates that in this case, the human operator would take a more supervisory role, since the level of trust in a fully automated treatment procedure was reported as very low. In case something went wrong, the human operator would not mind taking over the automated procedure, therefore, the LOA would decrease. Interestingly, when asked about the preferred future LOA, the “Information acquisition” action stage and the “Information analysis” action stage were higher at level 8 than “Decision selection” action stage and “Action implementation” action stage at level 3. A more detailed analysis of the questionnaire is in the next few sections.

6.5.2 'Human-Automation' questionnaire

The "Human-Automation" questionnaire researched the user-automation interaction at the LDR prostate brachytherapy treatment. After the information on the personal background was collected, the following automaton-related issues were researched: Trust in automation, reliance on automation, the perceived reliability of equipment performance, automation-related issues (these could be applied to the present LDR brachytherapy system), and 'preferred LOA' (this could be applied to the future LOA system). The discussion of the results is written in a structured way rather than following the questions one after another.

The response rate of 32% could have been better, but it needs to be understood that the questionnaire was filled out in the participant's free time, and since all core team members have busy schedules, this was very difficult. Maybe the response would be higher if there were rewards given for each returned questionnaire.

Please note that the "Seeds implantation" stage referred to in the "Human-Automation" questionnaire refers to the "Treatment delivery" stage used throughout this thesis.

1. Personal background

All participants were aged between 25 and 44. The participants had averagely four years of training, and about ten years of overall experience. Interestingly, most of the participants participated in more than 50 LDR prostate brachytherapy cases in their career.

3. Trust in automation

The participants were familiar with the technology they were using, and also trusted it. All participants reported that they had enough training and most of them reported that they did know how to use the technology. Most of the time the participants were not afraid of using the technology, however, one participant reported that they were afraid of using it. This may have to do with their experience, skills, education, or it may also be related to trust in technology they are not entirely familiar with. All participants had a positive feeling about the technology, and trusted the functionality of the technology, as well as the technology network. Most of the participants were undecided when asked if they trust people more than machines. One participant, however, answered that they trust people more than machines. This may be an indicator that in the future, people's decision on who to trust more may change, e.g. when the LOA increases with the introduction of new, mixed automation technologies in the near future, and then again with the introduction of more advanced automated technologies with higher LOA when they are introduced in the more distant future. Most of the participants reported that their perception of trust in machines is not always constant, and it changes. This may be related to the reliability of the machines, e.g. in cases of inadequate machine feedback/output. They did not have preferences over trusting some machines in the operating theatre more than others. However, the participants would use some of the machines in the operating theatre more than others. For example, some participants would predominantly use TRUS and ultrasound more than other machines. And some participants would predominantly use the computer with specialised software (e.g. the "planning system"), and also be in charge of the printer/printing. At the same time, there were some machines the participants would not use at all, e.g. operating Mick® applicator, ultrasound, and never use the machines used and operated by Anaesthetist. This reflects the roles and responsibilities of the individual participants. All the participants trust the controls/controller on the technologies they use. When it comes to the TRUS probe, connected to the ultrasound and TRUS feedback, most participants fully trusted the visual feedback and information displayed on the TRUS and computer displays. Most of the participants would trust new and old machines they are using equally, and some would prefer to use the machines they are used to. This indicates that the participants trust the machines they are using at present more than the new machines, or machines they may not be familiar with. This would suggest a gradual development and introduction of new technologies, along with gradual development and introduction of LOA action stages, especially of "Information acquisition" and "Information analysis" action stages, since they add a lot in terms of perceiving and analysing the information presented on the TRUS display and/or on the computer display. Most of the participants reported that they were aware of the potential errors from the technology they use. This indicates that their knowledge of the machines is sufficient, and that they know what to do in case errors occurred.

4. Reliance on automation

Some of the participants reported that the equipment they use is fully reliable. Half of the participants, however, were undecided. Only a few participants reported that they can fully rely on the computer equipped with specialised computer software. This may be related to any of the automation-related issues, e.g. trust in using the computer and its software, not trusting the reliability of the equipment, or because they did not want to rely on it. Most of the participants could finish their tasks in a designated time.

When using TRUS, most of the participants agreed that they could fully rely on it. Most of the participants agreed that they could not do their work without the reliability of visual feedback from TRUS. TRUS is the main provider of visual feedback, and without this piece of equipment it would be very difficult to implant the radioactive seeds so efficiently. Together with the computer and its specialised software, they are the two core pieces of technology, which make the LDR prostate brachytherapy treatment effective. Furthermore, all participants fully rely on the information *displayed* on the ultrasound and computer displays, and on the type of information *available* to them on the ultrasound and computer display. These two features are very important with team decision making during the treatment planning, because they may give an indication on what needs to be redesigned in the future. On one hand it may mean that there is enough information displayed on both displays, and on the other hand, it may mean that the users select what kind of information is displayed to them, which is a perfectly good feature. Because TRUS feedback is so well developed in the present LDR prostate brachytherapy system, it may indicate higher LOA levels at the “Information acquisition” action stage.

The participants reported that they can fully rely on the brachytherapy template and the Mick® applicator. These items, however, are fully manual. However, despite being a fully manual piece of technology, the Mick® applicator can occasionally be faulty. For example, the handle can get stiff, parts get stuck, the seed cartridge does not entirely fit in when inserted, etc.

When the equipment is occasionally faulty, only half of the participants still trust using it. Again, this may have to do either with the trust in the equipment they use, or with the reliability of the equipment.

One half of the participants, who responded, reported that they thought the new equipment is more reliable than the machine they have been using for the last few years. The second half was undecided. This may again be related to trust in technology, or trust in the reliance on the new equipment and its features.

The participants reported 63.13% support of the brachytherapy seed implantation operations. This means that the perception of the automated equipment is fairly low, and that there is still some space for further automation of the operations. However, while only half of the participants agreed that the operations could be more automated, most of the participants' disagreed or were undecided when asked if they would like to have more automated support for the brachytherapy operations. This can be interpreted as the participants being opened towards more automation, but at the same time not really being sure about automation supporting their operations. And at the same time, most of the participants reported that they could not perform the brachytherapy operations without the automated equipment. Their reliance on the automated equipment was rated at almost 70%.

5. Perceived reliability of equipment performance

All participants agreed that TRUS gives them excellent visual feedback. Most of them agreed that it was easy to adjust TRUS to get better visual feedback, and that it was easy to recognise the quality of the video feedback on the TRUS and/or computer display. Most of the participants reported that they have had technical problems with TRUS and the TRUS printer in the past. However, they never had problems with the quality of TRUS print outs. More than one third of the participants would be confused if the information on TRUS and/or computer display was presented to them differently to what they are used to. Most of the participants were happy with the TRUS resolution on the display. All these points could also be taken as guidelines when re-designing/improving the TRUS.

Most of the participants reported that their decisions were based solely/partly on the visual feedback from the machine, e.g. TRUS, that the technology helps them with their decision making process, and that the only information feedback they receive from the machine(s) was through the displays (some also mentioned mechanical/electronic feedback). This can be linked to the previous section mentioning that TRUS is a vital piece of technology core team members are using as an input for information, and based on which they make decisions. It will be interesting to see these changes in the future, when more automated equipment provides options to core team members to choose from, and what such changes this will bring to their perceived workload levels and TLX dimension proportions of the perceived workload.

All participants agreed that the equipment available in the operating theatre allows them to finish their operations in the designated time, and that it improves the quality of the brachytherapy seeds delivery. This confirms that the automated equipment helps the operators with their performance. Furthermore, most of the participants agreed that the equipment increased their *Situation Awareness*. The definition of *Situation Awareness* was provided in the questionnaire. Most of the participants agreed that the machine’s output is always correct. This means that they trust the information presented on the display, e.g. the information provided by TRUS presented in real-time.

All participants responded that they felt confident when using the equipment. Most of them responded that by using the automated procedures they can save time. These two statements are really important, and they may indicate that in the near- or distant future, when the operations will be further semi- or fully automated, the automation is most likely going to reduce the time of the treatment.

Most of the participants reported that the technology available was easy to use, and that certain (parts of) technology could be more useful. This means that the participants may be the best source of information when redesigning and improving the technology. Half of the participants reported that treatment efficacy has improved since the treatment (or parts of) has been automated.

Most of the participants were not afraid to use some of the machines/equipment available in the operating theatre. The question is would they have sufficient skills and knowledge on how to use such equipment.

All participants reported that the equipment they use occasionally fails, e.g. Mick® applicator, printer, feedback case, stepper, software, etc. However, they disagreed that some errors the machines make are unavoidable. This means that the equipment could be designed to fail less often, or not to fail at all.

The participants rated their level of satisfaction of their performance regarding the brachytherapy seed implantation operations at 87%. The participants rated their perceived level of satisfaction of their performance with regard to the performance of technical equipment at 80% for the computer, and at 82% for TRUS. These were very good results which at the same time leave opportunities for further enhancement.

When it comes to the automated operations, most of the participants were undecided when asked if they preferred to have more or less brachytherapy operations automated. However, most participants liked the fact that their performance was continually supported by automation. Also, all participants reported that they felt the technology was very useful to them. This gives a very positive indication of how well the automated equipment is accepted among the participants, and it may help with the design guidelines of the future automated equipment.

Some participants reported that some of the automated equipment failed them. The examples they provided were printer running out of ink, disconnected feedback cable, paper jam, laptop feedback, video card malfunction, etc. These examples may also indicate the future design improvements. The improvements mentioned by the participants would save time of the LDR prostate brachytherapy treatment, and may also result in a different perception of workload levels and dimensions.

All participants would know how to respond if the available equipment failed. Most of the participants would not need help with resetting the equipment in the situations when it failed. This might confirm that adequate training is in place, as well as that the participants have an adequate knowledge of the automated equipment they are using. This however, may change in the future, with the change of the automated equipment and/or with the change of staffing levels. When asked if they would prefer to switch to manual mode rather than to continue getting help from the automated equipment, half of the participants responded they would, half responded they would not, and one was undecided. This is a very interesting response in terms of automation, and again can be either related to trust in automation, e.g. trusting full, semi-, or manual automation to handle the treatment process, perceived reliability to handle the equipment in the emergency situations, or to personal skill set, training and readiness to efficiently respond to the case of emergency. This is confirmed by most of the participants reporting that they would not prefer if automation handled everything in the emergency situation. This means that they would still keep the personal control of the treatment process rather than let automation handling it.
Most of the participants reported that they put more reliance on the machine, or on part of the machine, e.g. TRUS feedback. All participants reported that the equipment they use was beneficial to their performance.

The participants rated the reliability of the equipment in the operating theatre at 87% for TRUS, 82% for printer, and 87% for 3D imaging. These numbers may reflect the participant's experience with the equipment and their negative experience when it failed. This is another indicator that can be used when trying to improve the LDR brachytherapy treatment.

One half of the participants reported that the technology used for prostate seed brachytherapy is not very user specific, while the other half stayed undecided. Most of the participants reported that since using the available technology, the efficiency of their performance has increased. Most of the participants responded that the technology improved the safety of the treatment procedure since they have been using it, and that the flexibility of operations is enhanced. For example, they may have more options to choose from, e.g. in the 3D virtual model, they can set up different views and model the virtually implanted seeds to achieve the optimal dose distribution.

6. Automation related issues

Most of the participants reported that they would not feel better if the “Treatment delivery” stage was fully or partially automated. This can be explained as a fear of automation. If fear of automation was present, the users would often feel threatened that the machine or automation would fully replace their roles and responsibilities.
All participants expressed to keep the control over the fully or partially automated procedure. This confirms that in the future automated systems, the role of the operators will turn into a supervisory role of the treatment process. This confirms the question asked later, where all participants reported that they would still remain supervising the process if the “Treatment delivery” stage was fully automated. However, when asked if they would prefer to supervise the procedure rather than deliver the seeds by themselves, half of the participants were undecided, and a quarter disagreed. This can be explained as they do not clearly understand what exactly their supervisory role would be. It would take some time, and a gradual progression towards a more automated system, and for the participants to understand more about automation in order to accept it. The latter sentence goes well with most participants reporting that they would stay focused on the seeds implantation procedure even if it was fully automated. This may be due to the intervention in the case of emergency. However, if the “Treatment delivery” stage was fully automated, half of the participants reported that their focus would then be on “3D image feedback” and/or TRUS feedback. They also reported that they would still be relying on the visual feedback. This can be understood as they would still be relying on the same visual feedback in the future, in a more automated system, the same as in the present system. They would also like to have an influence on the procedure even though it was fully automated. This can be understood as they would still keep the control over the procedure, and this just confirms their preference to take over the supervisory role. Furthermore, half of the participants reported that their knowledge of brachytherapy would be different in case of full automation. It is probably a matter of time for the participants to up skill and to learn to operate newly introduced automated equipment. Most of the participants reported that they would not mind learning how to use new automated equipment. As a matter of fact, most of the

participants reported that it is easy to learn how to use the new LDR brachytherapy equipment. This confirms that they have to be up to date with the technology hardware and software, and they have to keep learning and adapting their knowledge to new products.

Most of the participants reported that automation supports (them with) their workload. One half of the participants reported that automation also allows them to do other (subsequent) operations during the procedure. This reflects the current LOA, where the automation supports the operators. However, they responded that automation is “taking their knowledge and expertise away”. This is an interesting statement, and it explains how opened the participants are towards new automation. However, in another question, most of the participants reported that a fully automated “Treatment delivery” stage would not impact their knowledge of the procedure. This again confirms that they would keep up to date with the latest technologies and procedures.

Most of the participants reported that they would not let automation handle everything (if it was safe), and that they do not fully trust automated procedures. More than a third of participants reported that switching from manual seeds delivery to the automated seeds delivery would be easy. Most of the participants reported that they would not mind switching from automated procedures back to manual in cases of emergency.

Half of the participants reported that there is more than just one correct way to deliver the seeds at the “Treatment delivery” stage. This confirms the participants’ knowledge of the treatment procedure. Most of the participants reported they would mind if the “Seeds plan” stage (the stage before the “Treatment delivery” stage) was fully automated. This may reflect the fear of their (subsequent) operations being automated, and the possibility of changed roles and responsibilities.

All participants reported that they use brachytherapy equipment on a regular basis. This explains their skill set, understanding of the brachytherapy procedure, and their involvement in the procedure. As reported at the beginning of the questionnaire, most of the participants completed or have participated in over 50 brachytherapy cases so far, therefore they should have a solid understanding of the treatment procedure.

Most of the participants reported that they are fully aware of the current hardware and software automation features available in the operating theatre. Most of the participants reported that they would not lose the autonomy or authority over the treatment procedure in case of full automation. Both, autonomy and authority are important factors in automation. Autonomy in automation means that the participants would like to make the decisions and act on them independently of automation. Authority in automation means that the participants would like to keep the control of the treatment procedure.

Only a quarter of the participants reported that they would not feel bored during the “Treatment delivery” stage, while the majority were undecided. Half of the participants reported that they would not feel excluded if the “Treatment delivery” stage was fully automated. A quarter of the participants, however, reported they would feel excluded. Most of the participants reported that they would not feel like they are doing something useful if the stage was fully automated. This can be explained that the participants are not fully aware of the workload-related issues that the automation could bring to their working environment.

Half of the participants reported they would not move on to other (subsequent) operations, but stay at the same (subsequent) operation. More than a third of the participants reported that their workflow would not be interrupted in the case of full automation.

7. Preferred ‘Levels of Automation’

It is interesting to see that at “Information sensing”, which is part of the “Information acquisition” stage in the ‘MLOA’, and at “Information processing”, which is part of the “Information analysis” stage in the ‘MLOA’, the participants selected to have ‘Level 8’ LOA, which is a highly automated LOA. The “Information acquisition” stage means that “the computer detects and registers data, informs only if asked”. The “Information analysis” stage means that “the computer applies cognitive functions only if asked".

For two other stages, "Decisions", which is part of the "Decision selection" in the 'MLOA', and "Actions", which is part of the "Action selection" in the 'MLOA', the participants selected a 'low-to-medium' 'Level 3' LOA. At both, "Decision selection" stage and at "Action implementation" stage, it means that "the computer narrows the selection down to a few".

The 'preferred LOA' indicate one of the first steps towards partially-automated LOA. The rapid change in the LOA at the "Information acquisition" and "Information analysis" 'MLOA' stages may indicate that the participants are already interested in the higher LOA, and this interest in the higher automation should be included immediately in the design of the future human-automation LDR brachytherapy equipment.

6.5.3 Future work and recommendations regarding human-automation issues in LDR prostate brachytherapy

Future work and recommendations regarding human-automation issues at LDR prostate brachytherapy:

- Target a larger study group to receive a larger response rate; unfortunately the target group for the human-automation questionnaire was quite small, as it included the research participants from only four hospital sites which participated in this study. A larger sample across more hospital sites may get better results with a higher response rate.
- Reliance on automation is high on the TRUS, TRUS display, computer software, and consequently the information presented on the computer display. These are the most 'advanced' pieces of equipment, upon which the "Seed implantation" relies on. Furthermore, the redesign of these two systems may require separation of the information *displayed* on the screen from the information *available* on the screen. This may result in a few

different screens, e.g. one TRUS screen featuring a 2D view, one screen featuring a 3D view, and one 'utility' screen featuring a 'combined predicted' results of TRUS and computer (simulation) to accommodate 3D virtual models in order to achieve optimal dose distribution.

- The redesign of the Mick® applicator would need to introduce more reliable applicator parts/elements, with a few automation features, e.g. an electronic counter of seeds in the cartridge, as well as a feature to have multiple cartridges available on the applicator itself (e.g. 3-5 cartridges with min. 10 seeds per cartridge), which would save seed application time, and reduce or eliminate the manual counting of the seeds applied.
- Trust issue in automation: "trust in automation" and "fear of automation" should be researched as personal traits; such research would require a larger sample among radiotherapy staff to determine if these two traits are brachytherapy specific issues, radiotherapy specific issues, or if they have to do with the healthcare industry in general.
- The development of technologies in terms of automation has to be gradual to accommodate human operators adapting to such development, to understand the process of automation, and to keep the issues such as trust in automation, reliance on automation, reliability of automation and human performance at satisfactory levels. This includes the gradual development of the LOA action stages, as well as gradual development of LOA itself. The 'preferred LOA' indicate that the LOA should first increase at "Information acquisition" action stage and "Information analysis" action stage. This would result in an intermediate automation stage in the near future, before the introduction of full automation in the distant future. The jump from intermediate automation to full automation would consequently change the active role of the human operator into a more supervisory role, at least at the two above mentioned action stages. The development of "Decision selection" action stage and "Action implementation" action stage should be even more gradual, and should reflect the needs and preferences of the human operators, that is, the core team members' preferences. Along with the gradual development of automation, issues such as automation authority and automation autonomy should be taken into the account respectively.

- The brachytherapy technologies should be designed to accommodate switching between the fully- automated “Seed implantation” equipment to semi- automated equipment in emergency situations to avoid compromising the patient safety. However, this would require the core team members to be highly familiar and highly skilled with both, fully- and semi-automated procedures.
- TRUS technology could be combined with other technologies in the future to deliver even better screen resolution and therefore decrease the treatment time. We may see the TRUS technology in the future combined with sonic waves, flouroscopy, and perhaps even merged with CT and/or MRI images.

6.6 Chapter summary

This chapter introduced the topics of automation-related issues, and researched these in a format of “Human-Automation” questionnaire. The following topics were researched: the user’s trust in automation, the user’s reliance on automation, the users’ reliability/performance, automation-related issues of using brachytherapy equipment, and “Preferred ‘Levels of Automation’”. The results were presented and discussed. The future work and recommendations regarding human-automation issues at LDR prostate brachytherapy were discussed. The full outcome of the “Human-Automation” questionnaire will be considered in the results summary section of this thesis.

Chapter 7: The investigation of the relationship between perceived workload and 'Modified Levels of Automation' in Low-Dose Rate prostate brachytherapy

7.1 Chapter overview

This chapter investigates the relationship between perceived workload and 'Levels of Automation' in Low-Dose Rate prostate brachytherapy. The average perceived workload score of the core team members were compared with the assessed 'Modified Levels of Automation' action stages. Pearson's Correlation Coefficient was used to determine the linear correlation between the two variables. After Levene's test for 'Homogeneity of variances', Hypotheses testing was performed for ANOVA or Mann-Whitney U test to accept or reject null or alternative hypotheses, based on the obtained calculated probability (p-value) for determining the statistical significance of the results. The results in this chapter answer the fourth research question: "How does perceived workload relate to the 'Modified Levels of Automation' in the present Low-Dose Rate prostate brachytherapy system?", and provides indicators on the fifth research question: "How will the perceived workload relate to the 'Modified Levels of Automation' in the future Low-Dose Rate prostate brachytherapy system?"

7.2 Introduction

As outlined in the previous chapters, the cases with low high workload, which may compromise patient safety, were identified by using a methodical approach. At the same time, after applying a 'Modified Levels of Automation' model to LDR prostate brachytherapy, the levels of automation had moderate LOA at some core team member's operations at 'Information acquisition' action stage, and low LOA at 'Information analysis', 'Decision selection' and 'Action implementation' action stages. Therefore, there may be some indicators that show the relationship between perceived workload and MLOA in the present LDR prostate brachytherapy system, which would help with optimising the present working process either by improving the perceived workload levels by decreasing or increasing perceived workload levels, or by increasing automation of the specific core team member's operations. This investigation of the relationship will answer the fourth research question: "How does perceived workload relate to the 'Modified Levels of Automation' in the present Low-Dose Rate prostate brachytherapy system?", and provide indicators to answer the fifth research question "How will the perceived workload relate to the 'Modified Levels of Automation' in the future Low-Dose Rate prostate brachytherapy system?"

7.3 Methods

The purpose of the investigation of the relationship between perceived workload and 'Modified Levels of Automation' was to examine if there is any correlation between the assessed perceived workload and the four action stages of the 'Modified Levels of Automation' model for each main core team member's operation in LDR prostate brachytherapy (calculated as an average value for each core team member separately). The methods used for investigating the relationship between perceived workload and 'Modified Levels of Automation' presented in Figure 7-1 were Pearson's Correlation Coefficient (in Tests 1 and 3). After Levene's test for 'Homogeneity of Variance', either Analysis of Variance (ANOVA) (and optionally its 'Least Significant Difference' (LSD) post-hoc test), or Mann-Whitney U test were used to determine the differences between groups (in Tests 2 and 4). Levene's test, ANOVA and Mann-Whitney U test included a hypothesis testing with $p < 0.05$. Figure 7-1 presents the research approach, and the possible outcome values this approach could have. Tests 1 and 2 were researching the relationship between the two above presented variables of the *present* LDR prostate brachytherapy treatment system. Tests 3 and 4 were researching the relationship of the *future* LDR prostate brachytherapy treatment system, which incorporated the 'MLOA' levels from the "Preferred 'Levels of Automation'" from Chapter 6.

Tables 7-1 to 7-5 present the estimated future 'MLOA' and estimated levels of the perceived workload for each core team member individually. As part of the experiment, it was estimated that the perceived workload will increase by 20% in the near future for each core team member, or would remain the same if it is close to, or if it reaches the 'red-line' levels as presented in the 'Revised workload rating scale'.

Figure 7-1 Methodical approach to investigating the relationship between perceived workload and 'Modified Levels of Automation'

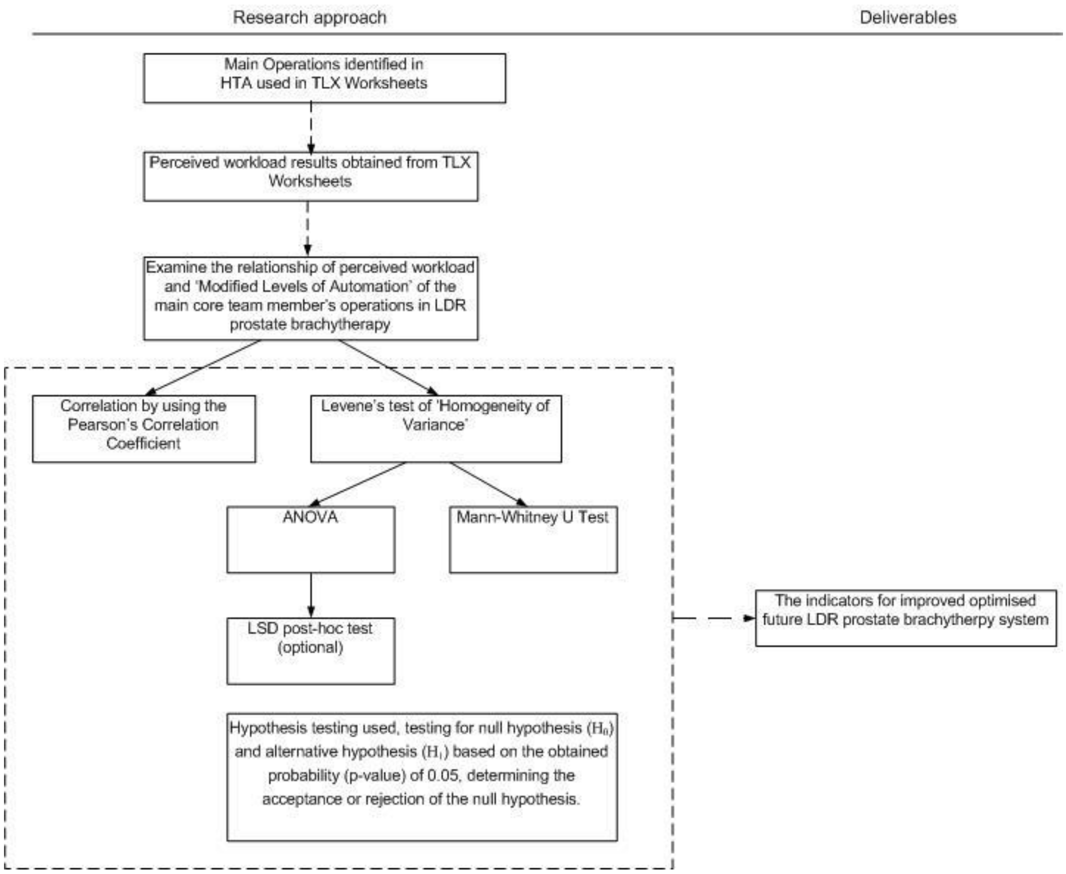


Table 7-1 The future 'MLOA' and estimated levels of perceived workload for Radiation oncologist & Radiologist

Operation	Information Acquisition	Information Analysis	Decision Selection	Action Implementation	Perceived workload (Rad. Oncologist & Radiologist, Site 1-4)
1	3	3	3	3	15.55
2	5	5	3	3	14.70
3	5	5	3	3	27.70
4	8	8	3	3	17.40
5	8	8	3	3	14.90
6	8	8	3	3	31.09
7	8	8	3	3	24.11
8	8	8	3	3	12.41

Table 7-2 The future 'MLOA' and estimated levels of perceived workload for Medical physicist #1

Operation	Information Acquisition	Information Analysis	Decision Selection	Action Implementation	Perceived workload (M.P. 1, Site 1-4)
1	3	3	3	3	34.45
2	8	8	3	3	32.10
3	8	8	3	3	48.10
4	8	8	5	5	40.94
5	8	8	5	5	45.58 *
6	8	8	5	5	45.85
7	5	5	5	5	29.86

** This estimated workload score remained unchanged*

Table 7-3 The future 'MLOA' and estimated levels of perceived workload for Medical physicist #2

Operation	Information Acquisition	Information Analysis	Decision Selection	Action Implementation	Perceived workload (M.P. 2, Site 1-4)
1	3	3	3	3	37.8
2	5	5	5	5	31.86
3	-	-	-	-	-
4	3	3	3	3	36.80
5	5	5	5	5	31.86 *

** This estimated workload score was lowered to the same level at on site 2*

Table 7-4 The future 'MLOA' and estimated levels of perceived workload for Nurse

Operation	Information Acquisition	Information Analysis	Decision Selection	Action Implementation	Perceived workload (Nurse, Site 1-4)
1	3	3	3	3	45.21 *
2	5	5	3	3	45.40

** This estimated workload score remained unchanged*

Table 7-5 The future 'MLOA' and estimated levels of perceived workload for Anaesthetist

Operation	Information Acquisition	Information Analysis	Decision Selection	Action Implementation	Perceived workload (Anaesthetist , Site 1-4)
1	3	3	3	3	43.44
2	8	8	3	3	33.85

Test 1: Present system

<u>Correlation</u>

Pearson's Correlation Coefficient was calculated to determine a linear relationship (the strength) between the following two variables: the average 'Perceived workload' scores of each core team member across all four hospital sites, and each action stage of the 'MLOA'.

If two variables are associated with each other, then the coefficient range (the strength) is between 1 (positive correlation), zero (no correlation), or -1 (negative correlation).

The degrees of freedom were calculated as df=n-2, where the "n" was the number of operations for each core team member.

The critical value or "r" (or $r_{critical}$) was determined as per Table VII "Values of the Correlation Coefficient for Different Levels of Significance" on p. 63 (Fisher and Yates 1938).

Test 2: Present system

<u>Levene's test</u>

Levene's test was performed to check for the 'Homogeneity of Variance' (if all the groups have the same or similar variance). Two hypotheses were tested with p <

0.05:

a) Null hypothesis: there is no difference between the variances of homogeneity (the variances are the homogeneous):
   H_0: $\mu_1 = \mu_2$
b) Alternative hypothesis: there is difference between the variances of homogeneity (the variances are not homogeneous):
   H_1: $\mu_1 \neq \mu_2$

Where the variances were homogeneous (by accepting the H_0), the ANOVA was used for a further analysis. Where the variances were not homogeneous (by rejecting the H_0), Mann-Whitney U test was used to determine the differences between the independent groups and the dependent variable.

ANOVA

ANOVA was calculated to determine the relationship between the following two variables: the average 'Perceived workload' scores of each core team member's operation across all four hospital sites, and each 'MLOA' action stage. Two hypotheses were tested with $p < 0.05$:

a) Null hypothesis: there is no difference between the levels of perceived workload and 'MLOA' (they are the same):
   H_0: $\mu_1 = \mu_2$
b) Alternative hypothesis: there is a difference between the levels of perceived workload and 'MLOA' (they are different):
   H_1: $\mu_1 \neq \mu_2$

The results of the ANOVA analysis are presented in the next section.

The LSD test was calculated to determine where the differences are between two individually compared groups after the H_0 in ANOVA was rejected. The result is significant when the difference is equal to, or larger than the LSD value.

Mann-Whitney U test

The Mann-Whitney U test was used to determine the differences between the medians of two data sets where ANOVA was not used. Two hypotheses were tested with $p < 0.05$:

a) Null hypothesis: there is no difference between the ranks of 'Perceived workload' and 'MLOA' action stage(s) (they are the same):
   H_0: $\mu_1 = \mu_2$
b) Alternative hypothesis: there is a difference between the ranks of 'Perceived workload' and 'MLOA' action stage(s) (they are different):
   H_1: $\mu_1 \neq \mu_2$

"U" statistic was calculated for each column, and compared to the $U_{critical}$ value, taking into the account the n-values ("n" being a sample size). The results of the Mann-Whitney U statistic are presented in the next section.

Test 3: Future system

Correlation

Pearson's Correlation Coefficient was calculated between the same two variables in the same manner as in Test 1. If two variables are associated with each other, then the coefficient range (the strength) between the two variables was determined between 1 (positive correlation), zero (no correlation), or -1 (negative correlation). The degrees of freedom were also calculated in the same manner as in Test 1, as df=n-2, where the "n" was the number of operations for each core team member. The critical value or "r" (or $r_{critical}$) was determined as per Table VII "Values of the Correlation Coefficient for Different Levels of Significance" on p. 63 (Fisher and Yates 1938). It was not possible to calculate Pearson's Coefficient for Radiation oncology nurse and Anaesthetist because their 'degrees of freedom' were too small.

Test 4: Future system

Levene's test

Levene's test was used in the same manner as in Test 2, including hypotheses testing with $p < 0.05$.

ANOVA

ANOVA was calculated in the same manner as in Test 2, including hypotheses testing with $p < 0.05$.

The LSD test was calculated in the same manner as in Test 2.

Mann-Whitney U test

The Mann-Whitney U test was used to in the same manner as in Test 2.

7.4 Results

7.4.1 The investigation of perceived workload and the 'Modified Levels of Automation' in "Low-Dose Rate" brachytherapy

The investigation of the relationship of 'Perceived workload' and 'MLOA' was trying to determine the statistical significance of the relationship between the two variables. Four tests were applied using Pearson's Correlation Coefficient, Levene's test, ANOVA (with the LSD test when applicable), and Mann-Whitney U test: Tests 1-2 were applied to the *present* LDR prostate brachytherapy treatment, and Tests 3-4 were applied to the theoretical '*future*' LDR prostate brachytherapy treatment, where a number of assumptions were made based on the results from the "Preferred 'Levels of Automation'" from Chapter 6 of this thesis. The results from the statistical analyses of the investigation of perceived workload and 'MLOA' in Low-Dose Rate brachytherapy are presented in Appendix I.

Test 1

The correlation between 'Perceived workload' and 'MLOA' was calculated for the average perceived workload values for each core team member's operation across all four sites, and the four 'MLOA' action stage levels assessed in one of the earlier chapters.

The Correlation Coefficient results were:

- Radiation oncologist & Radiologist: r = 0.35 for 'Information acquisition' action stage, and r=0.24 for all three other action stages; sample size=8; the df=6; p-value at 0.05=0.6319 (which is the critical value of "r")
- Medical physicists #1: r=0.64 for 'Information acquisition' action stage, and r=0.31 for all three other action stages; sample size=7; the df=5; p-value at 0.05=0.7545
- Medical physicists #2: r=0.40 for 'Information acquisition' action stage and 'Information analysis' action stage, and r=-0.54 for 'Decision selection' action stage and 'Action implementation' action stage: the df=3; p-value at 0.05=0.8783

The sample size for the Radiation oncology nurse and Anaesthetist was 2, and as a result, the 'degrees of freedom' were too small to calculate the correlation.

Test 2

<u>Levene's test</u>

Levene's test was conducted to determine the 'Homogeneity of Variance' (if the variances are equal across groups) at $p<0.05$, and to verify if ANOVA or Mann-Whitney U test should be used for further tests (marked with "X" if applicable, or with "N/A" if not applicable). The results of Levene's test are presented in Table 7-6.

Table 7-6 The results of Levene's test for 'Homogeneity of variance' for the present LDR prostate brachythearpy system

Core team member	Groups	Sample size	P-value	H_0 (accepted or rejected)	Answer	ANOVA	Mann-Whitney U test
Radiation oncologist & Radiologist	Site difference vs. Information acquisition & Information Analysis	8	0.00122	H_0 accepted	There *is* homogeneity of variance	X	N/A
	Site difference vs. Decision Selection & Action Implementation	8	5.73E-11	H_0 accepted	There *is* homogeneity of variance	X	N/A
Medical physicist #1	Site difference vs. Information acquisition & Information Analysis	7	0.00611	H_0 accepted	There *is* homogeneity of variance	X	N/A
	Site difference vs. Decision Selection & Action Implementation	7	0.00103	H_0 accepted	There *is* homogeneity of variance	X	N/A
Medical physicist #2	Site difference vs. Information acquisition & Information Analysis difference	5	0.0259	H_0 accepted	There *is* homogeneity of variance	X	N/A
	Site difference vs. Decision Selection & Action Implementation difference	5	0.0219	H_0 accepted	There *is* homogeneity of variance	X	N/A
Nurse	Site difference vs. All 'MLOA' action levels difference	2	5.74E-30	H_0 accepted	There *is* homogeneity of variance	X	N/A
Anaesthetist	Site difference vs. Information acquisition difference	2	0.182	H_0 rejected	There is *no* homogeneity of variance	N/A	X
	Site difference vs. Information Analysis, Decision Selection & Action Implementation difference	2	N/A	H_0 rejected	There is *no* homogeneity of variance	N/A	X

ANOVA

ANOVA analysis for the present 'MLOA' system was conducted to determine the differences (or similarities) between average perceived workload values and the 'MLOA' action stages for the following core team members: Radiation oncologist & Radiologist, Medical physics team, Radiation oncology nurse, and Anaesthetist. The results are presented in Table 7-7. The results of the LSD post-hoc test for the present system are presented in Table 7-8.

Table 7-7 The results of ANOVA analysis of perceived workload and 'MLOA' action stages for the present LDR prostate brachythearpy system

Core team member	**Sample size**	**Degrees of freedom**	**F-value**	**$F_{Critical}$**	**F (result)**	**P-value ($p < 0.05$)**	**H_0 (accepted or rejected)**
Radiation oncologist & Radiologist	5	4	44.07	2.64	$F > F_{Critical}$	3.38E-13	H_0 rejected
Medical physicist #1	5	4	114.17	2.69	$F > F_{Critical}$	1.06E-17	H_0 rejected
Medical physicist #2	5	4	75.43	2.87	$F > F_{Critical}$	8.94E-12	H_0 rejected
Nurse	5	4	120.48	5.19	$F > F_{Critical}$	3.71E-05	H_0 rejected
Anaesthetist	5	4	44.49	5.19	$F > F_{Critical}$	0.00042	H_0 rejected

Table 7-8 The results of the LSD post-hoc test for the present LDR prostate brachythearpy system

Core team member	**Sample size**	**Degrees of freedom (Within Groups)**	**Mean Square (Within Groups)**	**$t_{Critical}$ (Two- tailed) at p=0.05**	
Radiation oncologist & Radiologist	8	35	7.39	2.0301	
	Groups compared	**Mean difference**	**LSD**	**Mean difference ≥ LSD**	**H_0 (accepted or rejected)**
	Perceived workload and Information Acquisition	13.065	2.758	13.065 > 2.758	H_0 rejected

	Perceived workload and Information Analysis, Decision Selection and Action Implementation	14.566	2.758	14.566 > 2.758	H_0 rejected
Medical physicist #1	**Sample size**	**Degrees of freedom (Within Groups)**	**Mean Square (Within Groups)**	**$t_{Critical}$ (Two- tailed) at p=0.05**	
	7	30	12.47	2.042	
	Groups compared	**Mean difference**	**LSD**	**Mean difference ≥ LSD**	**H_0 (accepted or rejected)**
	Perceived workload and Information Acquisition	30.904	3.847	30.904 > 3.847	H_0 rejected
	Perceived workload and Information Analysis, Decision Selection and Action Implementation	32.189	3.847	32.189 > 3.847	H_0 rejected
Medical physicist #2	**Sample size**	**Degrees of freedom (Within Groups)**	**Mean Square (Within Groups)**	**$t_{Critical}$ (Two- tailed) at p=0.05**	
	4	20	14.859	2.085	
	Groups compared	**Mean difference**	**LSD**	**Mean difference ≥ LSD**	**H_0 (accepted or rejected)**
	Perceived workload and Information Acquisition & Information Analysis	33.278	5.081	33.278 > 5.081	H_0 rejected
	Perceived workload and Decision Selection & Action Implementation	33.678	5.081	33.678 > 5.081	H_0 rejected
Nurse	**Sample size**	**Degrees of freedom (Within Groups)**	**Mean Square (Within Groups)**	**$t_{Critical}$ (Two- tailed) at p=0.05**	
	2	5	5.45	2.570	
	Groups compared	**Mean difference**	**LSD**	**Mean difference ≥ LSD**	**H_0 (accepted or rejected)**

	Perceived workload and all four 'MLOA' action stages	40.51	5.998	40.51 > 5.998	H_0 rejected
Anaesthetist	* Mann-Whitney U test as per Levene's test				

Mann-Whitney U test

Following the Levene's test, the Mann-Whitney U test was conducted to compare the differences between two independent groups when the dependent variable was either ordinal or continuous, but is not normally distributed. The compared two groups were 'Perceived workload' values and the 'MLOA' action stages for the Anaesthetist (for present LDR prostate brachytherapy system). The results are presented in Table 7-10.

Table 7-9 The results of Mann-Whitney U test for or the present LDR prostate brachythearpy system

Core team member	Groups	Sample size	$U_{statistic}$	$U_{critical}$	Result	H_0 (accepted or rejected)	Answer
Anaesthetist (Present system)	Workload	2	8				
	Information acquisition & Information analysis	2	2.5				
	Decision selection & Action implementation	2	1.5				
	$U_{critical}$			0.333	1.5 > 0.333 $U_{stat} > U_{critical}$	H_0 accepted	There is *no* difference between the ranks

Test 3

The correlation between 'Perceived workload' and 'MLOA' was calculated in the same manner as in Test 1.

The Correlation Coefficient results were:

- Radiation oncologist & Radiologist: r = 0.12 for 'Information acquisition' and 'Information Analysis' action stages; it was unavailable for 'Decision selection' and 'Action implementation' action stages; sample size=8; the df=6; p-value at 0.05=0.6319 (which is the critical value of "r")
- Medical physicists #1: r=0.61 for 'Information acquisition' and 'Information analysis' action stages, and r=0.17 for 'Decision selection' and 'Action implementation' action stages; sample size=7; the df=5; p-value at 0.05=0.7545
- Medical physicists #2: r= -0.99 for all action stages; sample size=4; the df=2; p-value at 0.05=0.95

There was no significant difference in the correlation between the 'Perceived workload' and 'MLOA' action stages among Radiation oncologist & Radiologist, and Medical physicist #1. There was, however, enough statistical evidence to report $r_{critical}$>r for Medical physicist #2, who had a strong negative correlation of -0.99. Similar to Test 1, it was not possible to calculate the correlation for Radiation oncology nurse and Anaesthetist because their 'degrees of freedom' were too small to calculate the correlation.

Test 4

Levene's test

Levene's test was conducted to determine the 'Homogeneity of Variance' (if the variances are equal across groups) at p<0.05, and to verify if ANOVA or Mann-Whitney U test should be used for further tests. The results of Levene's test are presented in Table 7-10.

Table 7-10 The results of Levene's test for 'Homogeneity of variance' for the future LDR prostate brachythearpy system

Core team member	Groups	Sample size	P-value	H_0 (accepted or rejected)	Answer	ANOVA	Mann-Whitney U test
Radiation oncologist & Radiologist	Site difference vs. Information acquisition & Information Analysis	8	0.00118	H_0 accepted	There *is* homogeneity of variance	X	N/A
	Site difference vs. Decision Selection & Action Implementation	8	3.70E-05	H_0 accepted	There *is* homogeneity of variance	X	N/A
Medical physicist #1	Site difference vs. Information acquisition & Information Analysis	7	0.000953	H_0 accepted	There *is* homogeneity of variance	X	N/A
	Site difference vs. Decision Selection & Action Implementation	7	0.000195	H_0 accepted	There *is* homogeneity of variance	X	N/A
Medical physicist #2	Site difference vs. All 'MLOA' action levels difference	5	0.000148	H_0 accepted	There *is* homogeneity of variance	X	N/A
Nurse	* Mann-Whitney U test as per Levene's test						
Anaesthetist	Site difference vs. Information acquisition difference	2	2.80E-30	H_0 accepted	There *is* homogeneity of variance	X	N/A
	Site difference vs. Information Analysis, Decision Selection & Action Implementation difference	* Mann-Whitney U test as per Levene's test					

ANOVA

ANOVA analysis for the future 'MLOA' system was conducted to determine the differences (or similarities) between the perceived workload and the 'MLOA' action stages. The ANOVA was conducted in the same manner as in Test 2. The results are presented in Table 7-11. The results of the LSD post-hoc test for the future system are presented in Table 7-12Table 7-12.

Table 7-11 The results of ANOVA analysis of perceived workload and 'MLOA' action stages for the future LDR prostate brachythearpy system

Core team member	**Sample size**	**Degrees of freedom**	**F-value**	**$F_{Critical}$**	**F (result)**	**P-value ($p < 0.05$)**	**H_0 (accepted or rejected)**
Radiation oncologist & Radiologist	5	4	34.1	2.64	$F > F_{Critical}$	1.26E-11	H_0 rejected
Medical physicist #1	5	4	125.9	2.69	$F > F_{Critical}$	2.69E-18	H_0 rejected
Medical physicist #2	5	4	243.37	3.05	$F > F_{Critical}$	1.91E-13	H_0 rejected
Nurse	5	4	870.6	5.19	$F > F_{Critical}$	2.72E-07	H_0 rejected
Anaesthetist	5	4	33.56	5.19	$F > F_{Critical}$	0.00083	H_0 rejected

Table 7-12 The results of the LSD post-hoc test for the future LDR prostate brachythearpy system

Core team member	**Sample size**	**Degrees of freedom (Within Groups)**	**Mean Square (Within Groups)**	**$t_{Critical}$ (Two- tailed) at $p=0.05$**	
Radiation oncologist & Radiologist	8	35	11.215	2.0301	
	Groups compared	**Mean difference**	**LSD**	**Mean difference ≥ LSD**	**H_0 (accepted or rejected)**
	Perceived workload and Information Acquisition & Information Analysis	13.107	3.398	13.107 > 3.398	H_0 rejected
	Perceived workload and, Decision Selection & Action Implementation	16.732	3.398	16.732 > 3.398	H_0 rejected

Medical physicist #1	**Sample size**	**Degrees of freedom (Within Groups)**	**Mean Square (Within Groups)**	**$t_{Critical}$ (Two- tailed) at p=0.05**	
	7	30	12.998	2.042	
	Groups compared	**Mean difference**	**LSD**	**Mean difference ≥ LSD**	**H_0 (accepted or rejected)**
	Perceived workload and Information Acquisition	32.697	3.928	32.697 > 3.928	H_0 rejected
	Perceived workload and Information Analysis, Decision Selection and Action Implementation	35.412	3.928	35.412 > 3.928	H_0 rejected
Medical physicist #2	**Sample size**	**Degrees of freedom (Within Groups)**	**Mean Square (Within Groups)**	**$t_{Critical}$ (Two- tailed) at p=0.05**	
	4	15	3.074	2.131	
	Groups compared	**Mean difference**	**LSD**	**Mean difference ≥ LSD**	**H_0 (accepted or rejected)**
	Perceived workload and all four 'MLOA' action stages	30.581	2.64	30.581 > 2.64	H_0 rejected
Nurse	**Sample size**	**Degrees of freedom (Within Groups)**	**Mean Square (Within Groups)**	**$t_{Critical}$ (Two- tailed) at p=0.05**	
	2	5	0.803	2.570	
	Groups compared	**Mean difference**	**LSD**	**Mean difference ≥ LSD**	**H_0 (accepted or rejected)**
	Perceived workload and all four 'MLOA' action stages	41.303	2.302	41.303 > 2.302	H_0 rejected
Anaesthetist	**Sample size**	**Degrees of freedom (Within Groups)**	**Mean Square (Within Groups)**	**$t_{Critical}$ (Two- tailed) at p=0.05**	
	2	5	14.192	2.570	

	Groups compared	Mean difference	LSD	Mean difference ≥ LSD	H_0 (accepted or rejected)
	Perceived workload and Information Acquisition & Information Analysis	33.146	9.681	33.146 > 9.681	H_0 rejected
	Perceived workload and Decision Selection & Action Implementation	35.646	9.681	35.646 > 9.681	H_0 rejected

Mann-Whitney U test

In the same manner as in Test 2, following the Levene's test, the Mann-Whitney U test was conducted to compare the differences between two independent groups when the dependent variable is either ordinal or continuous, but is not normally distributed. The compared two groups were 'Perceived workload' values and the 'MLOA' action stages for the Radiation oncology nurse and Anaesthetist (for future LDR prostate brachytherapy system). The results are presented in Table 7-13.

Table 7-13 The results of Mann-Whitney U test for the future LDR prostate brachythearpy system

Core team member	Groups	Sample size	$U_{statistic}$	$U_{critical}$	Result	H_0 (accepted or rejected)	Answer
Anaesthetist (Future system)	Workload	2	4				
	Decision selection & Action implementation	2	0				
	$U_{critical}$			0.333	0 ≤ 0.333 $U_{stat} \leq U_{critical}$	H_0 rejected	There *is* difference between the ranks
Nurse (Future system)	Workload	2	8				
	Information acquisition & Information analysis	2	3				
	Decision selection & Action implementation	2	1				

Core team member	Groups	Sample size	$U_{statistic}$	$U_{critical}$	Result	H_0 (accepted or rejected)	Answer
	$U_{critical}$			0.333	1 > 0.333 U_{stat} > $U_{critical}$	H_0 accepted	There is *no* difference between the ranks

7.5 Discussion

7.5.1 The main findings of this chapter

The investigation of the relationship between average TLX scores of perceived workload assessed the core team members and the 'Modified Levels of Automation' action stages. Pearson's Correlation Coefficient found a small correlation among the Radiation oncologists & Radiologists and moderate correlation among the Medical Physics team in the present LDR prostate brachytherapy treatment system, with a very weak statistical significance. There was, however a strong negative correlation between the two variables obtained for the Medical physicist #2 in the future LDR prostate brachytherapy system. Levene's test of 'Homogeneity of variances' has shown that most of the groups were homogenous, and therefore ANOVA was used in most cases (and the LSD post-hoc test where applicable). ANOVA has shown that there is a difference between the levels of 'Perceived workload' and 'MLOA'. Where the groups were not homogeneous, Mann-Whitney U test was performed. The Mann-Whitney U test has shown that there was no difference between perceived workload and 'MLOA' ranks.

7.5.2 Researching the relationship between perceived workload and 'MLOA' action stages in LDR prostate brachytherapy in the present 'MLOA' system

The data used for perceived workload used was calculated as an average TLX score for each core team member's operation separately. This data was then used for the calculation of Pearson's Correlation Coefficient (Test 1) and ANOVA (Test 2) in the present 'MLOA' system.

Test 1

A small correlation was found at all four 'MLOA' action stages among the Radiation oncologists & Radiologists. Moderate correlation was found among the Medical Physics team at the 'Information acquisition' action stage, and weak correlation was found at the other three 'MLOA' action stages in the present LDR prostate brachytherapy treatment system. However, there was not enough evidence to state that there was a significant linear relationship between the 'Perceived workload' and 'MLOA' action stages. This means that increases or decreases in 'Perceived workload' do not significantly relate to the increases or decreases in 'MLOA'.

Radiation oncologist & Radiologist

There was a small correlation between 'Perceived workload' at all 'MLOA' action stages, but it was not statistically significant ($r_{critical}<r$).

Medical physicists #1

There was a moderate correlation between the 'Perceived workload' and 'Information acquisition' action stage, and a small correlation between the other three 'MLOA' action stages, but were statistically not significant ($r_{critical}<r$).

Medical physicists #2

There was a small correlation between the 'Perceived workload' and 'Information acquisition' action stage, and 'Perceived workload' and 'Information analysis' action stage, but it was not statistically significant ($r_{critical}<r$). There was a small correlation between the 'Perceived workload' and 'Decision selection', and the 'Perceived workload' and 'Action implementation' action stage, but it was again statistically not significant ($r_{critical}<r$).

Test 2

Levene's test

Levene's test determined that there is homogeneity of variance between scores for most of the 'Perceived workload' and 'MLOA' data. It verified if ANOVA or Mann-Whitney U test should be used for further tests. In all but one case, H_0 was accepted, which indicated that ANOVA can be used for further analysis. The one case where H_0 was rejected was in case of Anaesthetist at 'Perceived workload' vs. 'Decision Selection' & 'Action Implementation' 'MLOA' action stage.

ANOVA

The ANOVA analysis for Radiation oncologist & Radiologist, Medical physicist #1, Medical physicist #2, Radiation oncology nurse, and Anaesthetist has shown that $F > F_{critical}$ in all cases, therefore all H_0 were rejected, meaning the variance between two means was significantly different in the present LDR prostate brachytherapy system. Also, the p-values were smaller than 0.05, which meant that the p-values confirmed that the differences were statistically significant, and that H_0 was rejected: there is a difference between the levels of 'Perceived workload' and 'MLOA'. The LSD post-hoc tests confirmed that there is a statistical significance that the H_0 can be rejected. This means there is a difference between 'Perceived workload' and all four 'MLOA' action stages in the present system.

Mann-Whitney U test

As mentioned above, the Mann-Whitney U test was used to determine the differences between the medians of two data sets where ANOVA was not used. In the case of present LDR prostate brachytherapy, this was for Anaesthetist, for values of 'Perceived workload' vs. 'Information Acquisition', and 'Perceived workload' vs. the other three 'MLOA' action stages. The H_0 accepted, meaning that there was no difference between the workload and 'MLOA' ranks. In this case the result may reflect a very small sample size (of 2), and because of this, it may be very difficult to detect the differences between the two samples, even if the H_0 was accepted.

7.5.3 Researching the relationship between perceived workload and 'MLOA' action stages in LDR prostate brachytherapy in the future 'MLOA' systems

The data used for hypothesis testing of the relationship between perceived workload and 'MLOA' action stages was based on a number of assumptions:

- As part of the experiment, it was estimated that the perceived workload will increase by 20% in the near future for each core team member, or it would remain the same if it is close to, or if it reaches the 'red-line' levels.
- Based on the research on the "Preferred 'LOA'" in Chapter 6 of this thesis, the change in automation would be shown as an increase in 'MLOA' especially at the 'Information acquisition' and 'Information analysis' action stages, where the 'MLOA' is predicted to raise to Level 8, which would mean that the operations of the core team members will change in the future.
- Because some operations are going to be automated, they will disappear as an operation from the present LDR prostate brachytherapy system, e.g. "Seeds evaluation form" operation, currently performed by the Medical physicist #2.

These assumptions only refer to the 'MLOA' that are going to be in the near future, as part of the 'next' step in the development of automation. It is assumed that in the distant future, 'MLOA' levels will increase even further in the other 'MLOA' action stages, as well as there will be a change in the number of the operations performed by the core team members, which will most possibly result in an operation decrease and the 'MLOA' increase. As part of this experiment, the number of operations of the core team members stayed the same, with the exception of the "Seed evaluation form" operation for Medical physicist #2, which was taken out as part of the 'future' automation.

Some of the estimated workload scores remained unchanged, if they were close to the 'Red-line' levels as per the 'Revised workload rating scale'. The data for the estimated future 'MLOA' and estimated levels of perceived workload for each core team member are presented in Tables 7-1 to 7-5. This data was then used for the calculation of Pearson's Correlation Coefficient (Test 3) and ANOVA (Test 4) in the future 'MLOA' system.

Test 3

Similar to Test 1, there was a slight, but not significant correlation between the 'Perceived workload' and 'MLOA' action stages among the Radiation oncologists & Radiologists, and slight to moderate, but not significant correlation between the 'Perceived workload' and 'MLOA' action stages for Medical physicists #1 in the future LDR prostate brachytherapy treatment system. Similarly to Test 1, this means that increases or decreases in 'Perceived workload' do not significantly relate to the increases or decreases in 'MLOA'. However, there was a very strong correlation between 'Perceived workload' and all four 'MLOA' action stages for Medical physicists #2. This means that increases or decreases in 'Perceived workload' do significantly do relate to the increases or decreases in 'MLOA' in the future 'MLOA' systems.

Radiation oncologist & Radiologist

There was a slight correlation between the 'Perceived workload' and 'Information acquisition' action stage, and 'Perceived workload' and 'Information analysis' action stage, but it was not statistically significant ($r_{critical}<r$).

Medical physicists #1

There was a moderate correlation between the 'Perceived workload' and 'Information acquisition' action stage, and 'Perceived workload' and 'Information analysis' action stage, and a slight correlation between 'Perceived workload' and 'Decision selection' action stage, and 'Perceived workload' and 'Action implementation' action stage. However, all correlations were not statistically significant ($r_{critical}$<r), which means that there was not enough evidence of an association between two the 'Perceived workload' and 'MLOA' action stages. Statistical significance could perhaps be reached with a larger sample, or bigger changes in perceived workload or the assessed 'MLOA' action stages.

Medical physicists #2

There was a very strong negative correlation between the 'Perceived workload' and all four 'MLOA' action stages. The correlation was statistically significant at p-value of 0.05 ($r_{critical}$>r), though the 'degrees of freedom' were reported as very low at "df=2". It would be interesting to see the correlation with a larger data sample, e.g. with the 'degrees of freedom' of "10" or more.

However, based on our current data, the strong negative correlation may explain two assumptions regarding the future LDR prostate brachytherapy systems:

- In the near and distant future, the operations and sub-operations of the core team members will change, and this will most probably also bring the changes to the core team members' roles and responsibilities.
- Since some of the operations and sub-operations performed in the present LDR prostate brachytherapy system will not exist any more because they will become more automated, the core team members will most likely be performing different operations and sub-operations in the near and distant future compared to the present LDR prostate brachytherapy system.
- The change in performing different operations and sub-operations in the near and distant future will most probably change the levels of perceived workload. As part of this experiment, a slight increase in the levels of perceived workload was estimated (in our case, this was a 20% increase). The changes among the core team members might consequently mean that the time core team members spend in the operating theatre during the LDR prostate brachytherapy treatment may change, and they could spend more time on other tasks.

Test 4

Levene's test

Levene's test determined that there is homogeneity of variance between scores for most of the 'Perceived workload' and 'MLOA' data. It verified if ANOVA or Mann-Whitney U test should be used for further tests. In all but one case, H_0 was accepted, which indicated that ANOVA can be used for further analysis. The one case where H_0 was rejected, was in case of Anaesthetist.

ANOVA

ANOVA analysis for the future 'MLOA' system was conducted in the same manner as for Site 2. Unfortunately, similar to Test 2, Test 4 could not determine any differences (or similarities) between the perceived workload and the 'MLOA' action stages. Similarly to the Test 2, the LSD post-hoc tests also confirmed that there is a statistical significance that the H_0 can be rejected. This means there is a difference between 'Perceived workload' and all four 'MLOA' action stages in the future system. Perhaps this will change in the near and distant future, when more operations are automated, and will have higher 'MLOA'.

Mann-Whitney U test

Similar to the results in Test 2, Mann-Whitney U test determined that there was difference between the ranks for Anaesthetist (H_0 was rejected), and that there was no difference between the ranks for radiation oncology nurse (H_0 was accepted). For larger samples this may be an important factor, but in our case, the sample size was very small (n=2), and therefore the power to determine statistical significance was very low, even though H_0 was accepted. For future reference, it is recommended that the sample sizes are larger for more powerful increased statistical significance.

7.5.4 Research limitations of the investigation of the relationship between perceived workload and 'Levels of Automation' model in LDR prostate brachytherapy

The research limitations related to the investigation of the relationship between 'Perceived workload' and the four 'MLOA' action stages based on the 'Modified 'Levels of automation' for LDR prostate brachytherapy include:

- The correlation between the 'Perceived workload' and 'MLOA' was only based on the current 'Levels of Automation'; how these two variables will change in the future may be different to how they are presented in our research.
- Some sample sizes were relatively small, and consequently the degrees of freedom. The results may have been different with larger sample sizes, e.g. if the data was collected from more hospital sites, or if more operations and/or sub-operations were taken into the account.
- Several assumptions were taken into account when calculating ANOVA, including the assumption that there is homogeneity of variances, meaning that the population variances in each group are equal.
- In the near and distant future, the correlation between the 'Perceived workload' and 'MLOA' may change every time the 'MLOA' changes. This presents limitations at two levels:

    - The change in the 'MLOA' *action stages*: In the present LDR prostate brachytherapy system, the highest 'MLOA' levels are at the "Information acquisition" action stage. Based on the suggested "Preferred 'Levels of Automation'" scenario for the future system, any of the 'MLOA' action stages can change, but most likely it will be the 'Information acquisition" and "Information analysis' action stages that will change first, and then gradually, followed by the change of the other two action stages in the "near" and "distant" future, until the 'full' automation is reached in all 'MLOA' action stages.

- The individual 'MLOA' *levels*: The 'MLOA' in this research only assessed 'MLOA' of the present system, and based on the "Preferred 'Levels of Automation'" also provided indications on how the 'MLOA' will change in the future systems. Based on the data in our research, the 'MLOA' levels will most likely change first at the "Information acquisition" and "Information analysis" action stages, where it may reach levels 8-10a in the 'near' and 'distant' future, gradually followed by the other two action stages. The changes in the 'MLOA' levels will nevertheless reflect the future design and technology advancement.

This investigation of the relationship between perceived workload and the 'MLOA' has demonstrated that there is not enough evidence to state that a strong linear relationship exists in the data between the 'Perceived workload' and 'MLOA' in the present LDR prostate brachytherapy system, but there may be some correlation between the two variables in the future LDR prostate brachytherapy system (assumptions were provided as part of the results from Test 3). This answered the fourth and final research question: "How will the perceived workload relate to 'MLOA' in the future LDR prostate brachytherapy system?"

7.5.5 Future work and recommendations for automation and 'Levels of Automation' in LDR prostate brachytherapy

Future work and recommendations for automation and 'Levels of automation' in LDR prostate brachytherapy:

- The 'MLOA' should be applied to every present and future technology in the radiotherapy domain. Hospitals should be aware that new technology may change people's perception, their performance, and consequently even staffing levels. They should also be aware that the staff may have to expand their skills and upgrade their knowledge just to keep up with the latest technologies. The track record of the applied 'MLOA' should be kept together with the staff performance reports.

- The development of radiotherapy equipment should be gradual in order to fit the human adaptation to such equipment. This includes careful observation of the advancement, or development of the 'MLOA' action stages from predominantly low automation (at present), to moderately mixed automation (in the near future), and eventually to full automation (in the distant future). The development and the introduction of the new radiotherapy equipment may, however, introduce new trends with regards to human errors in radiotherapy (Fallon, Galičič et al. 2015).
- The automation in the distant future will most probably change the number of the core team members, as well as their operations as sub-operations. The role of Radiation oncologist and Radiologist will most probably move to the supervisory mode, because the specific operations, such as "Needle implantation", "Peripheral seeding and planning" and "Central seeding and planning" will be highly automated, e.g. even to the Level 10a as described in the 'MLOA' model. The examples of such robotic systems can be found in the literature, e.g. in the research performed by Davies et al. (2004), Yu et al. (2007), Fichtinger et al. (2008), Hungr et al. (2009), and Buzurovic (2010), who were researching the robot-assisted systems for needle and seed implantation in LDR prostate brachytherapy.
- The progress in providing the high resolution of imaging provided by TRUS will most likely improve the "Treatment delivery" stage of the LDR prostate brachytherapy treatment process. The visual feedback provided by more automated software, designed to fit its use, and powered by super-fast hardware, will be more automated, or will offer more automation options, as the time progresses. This will most probably result in the change of operations and sub-operations performed by the Radiation oncologist and Medical physics team, as well as their roles and responsibilities.

7.6 Chapter summary

This chapter investigated the relationship between perceived workload and 'Levels of Automation' in Low-Dose Rate prostate brachytherapy. The average perceived workload values from each core team member's main operation were compared with the assessed 'MLOA' action stages. The data was analysed by using Pearson's Correlation Coefficient and ANOVA. Hypotheses testing tested the null hypothesis (H_0) and alternative hypothesis (H_1) at p-value of 0.05. The results identified no correlation between the two variables in the present LDR prostate brachytherapy system, and that it is possible that there will be some correlation between these two variables in one of the future 'MLOA' models. A short experiment of the future 'MLOA' model was based on the "Perceived 'Levels of Automation'" 'MLOA' levels, presented in Chapter 6 of this thesis. This chapter therefore answered the fourth research question: "How does perceived workload relate to the 'Modified Levels of Automation' in the present Low-Dose Rate prostate brachytherapy system?", and also provided an indication on answering the fifth research question: "How will the perceived workload relate to the 'Modified Levels of Automation' in the future Low-Dose Rate prostate brachytherapy system?" However, the fifth research question will be explored further in the next chapter.

Chapter 8: General discussion and application of perceived workload and 'Levels of automation' to future automation systems

8.1 Chapter overview

This chapter provides a general discussion to this research focussing on the application of perceived workload and 'Levels of automation' of the present and future LDR prostate brachytherapy systems. This chapter answered the fifth research question: "How will the perceived workload relate to the 'Modified Levels of Automation' in the future Low-Dose Rate prostate brachytherapy system?"

8.2 Guidelines and recommendations for present and future LDR prostate brachytherapy systems

The focus of guidelines and recommendations for the improvement of the LDR prostate brachytherapy treatment are based on the research performed in this thesis. They incorporate human-automation aspects and are written from the human-centred Human Factors Engineering perspective. People from other backgrounds may provide different recommendations. These guidelines and recommendations were written for both, present and future LDR prostate brachytherapy systems:

Present system

a) The core team

- Perceived workload: The current research study assessed the perceived workload of the core team members. These results can serve as design guidelines of the near- or distant- future automated technologies. The purpose of such designs would be to keep perceived workload at 'optimal' levels, and to make sure there are no operations which would cause the situations where the workload is too low or too high. The study of the TLX dimensions can help the designers to target the percentage proportions of the specific dimensions to fit them to the users more easily.

- In the first instance, the perceived workload levels will most probably be different if patient-related issues, e.g. pubic arch interference, prostate gland skewness, etc., were (re)solved with the help of technology. Also, if the current automation-related issues, e.g. problems with the cable, TRUS/ultrasound usability, the design of the stepper, Mick® applicator, cartridges, etc. were solved in the present system, the perceived workload results may also have been different.

b) The technologies:

- Stepper: To be designed for the left- and right-handed persons; at the moment the stepper appears to be designed only for the right-handed people.
- Cartridge: An automated seed counter could be introduced to count the number of seeds in the cartridge, and the number of seeds that were implanted, that is, a number of seeds which passed the tip of the needle.
- Mick® applicator: An automated seed counter could be installed to keep track of the radioactive seeds externally (while in the seed cartridge) and internally (once they are implanted into the patient's prostate gland). It also needs to be redesigned not to allow the seeds to get stuck, or that parts of the applicator would malfunction.
- Ultrasound: Larger, wider display is needed for the ultrasound for the operators to follow the feedback more easily. Alternatively, an additional display would present a longitudinal view of the prostate gland on the first display, and a latitudinal view of the prostate gland on the second display. This would make the information perception easier, it could help with decision making, which would overall save time. There should also be an option for a separate portable screen or a tablet to be set up above the template, as a separate display to

TRUS. This would save time needed to turn the head/neck on the side to look at the TRUS display, and would therefore make the seed implantation much faster, e.g. for Radiation oncologist.

- Computer: Separated keyboard, mouse, display and computer on an ergonomically designed desk would give enough space for the hands and improve the overall posture. Additional displays would allow for easier, faster and more efficient virtual modelling. The software could be simplified. The cables need to be redesigned; a wireless transfer of data between the ultrasound and computer may create more space on the floor.
- Printer: It should be using two interchangeable cartridges and paper trays, which would make printing more convenient and would avoid paper jams.

c) Levels of Automation

Levels of Automation: On one hand, some core team's operations in the present system are performed manually, which is 'Level 1' in the 'Modified Levels of Automation' (MLOA) model, which corresponds to low LOA. These operations have mostly to do with the set-up and preparation before the treatment is started, and are the same in the "Loose seeds" and "Stranded seeds" LDR prostate brachytherapy. E.g. the Radiation oncologist setting up the TRUS, which has to be inserted with the hands, and adjusting the TRUS to the best angle in order to achieve the most optimal visual feedback (or places the catheter and positioning the ultrasound in "Stranded seeds" LDR prostate brachytherapy). Medical physicist #1 performs the QA on the radioactive seeds together with Medical physicist #2, which is done completely manually (apart from using the calculator for the calculations). Then Medical physicist #1 sets up the computer, TRUS, and syncs their connectivity. In the mean time, Medical physicist #2 moves on to a completely manual pen & paper "Seeds evaluation form" operation (this corresponds to the "Loose seeds" LDR prostate brachytherapy). In the "Stranded seeds" LDR prostate brachytherapy, the Medical physicist #1 performs prostate volume study, plan and plan printing, and real time check, while the role of the Medical physicist #2 remains to perform room

monitoring. Similarly, Nurse and Anaesthetist also prepare the items for the treatment manually in both types of LDR prostate brachytherapy treatment, e.g. the Nurse prepares the stepper, patient's bed, disposable needles, etc, The Anaesthetist checks the equipment, prepares anaesthetic drugs, positions/sets up the patient, etc.
On the other hand, some operations are performed with a combination of low and medium automation. Some operations have 'Level 2' in all four MLOA action stages of 'MLOA' which is still a fairly low LOA. For example, the Radiation oncologist measures the prostate volume with TRUS, implants needles based on the visual feedback from TRUS, and at some sites, also measures prostate volume post implant. However, some other operations, for example "Volume post needle", "Virtual prostate and urethra positioning", "Peripheral seeding and planning", and "Central seeding and planning" have 'Level 2' at three action stages: 'Information Analysis', 'Decision selection' and 'Action implementation', but not at 'Information acquisition'. Similarly, 'Level 2' was assessed at all action stages for Medical physicist #1 at "Measure volume" and "Volume post needle" operations, when the prostate volume gets measured, following the Radiation oncologist's steps with the specialist software. The same 'Level 2' is assessed at other operations (e.g. operations 4-7) at the same action stages as at the Radiation oncologist, with the exception of 'Information acquisition' stage, which is higher. The 'MLOA' is different for the operations performed by Medical physicist #2, where the G-M counter is used to scan for a radioactive source just by turning it on and off, and all action stages remain unchanged. The Anaesthetist's role during the "Patient monitoring" operation is predominantly supervisory, and similarly to the role of the Radiation oncologist, the 'Information analysis', 'Decision selection', and 'Action implementation' action stages have MLOA assessed ad 'Level 2', whereas it is higher at 'Information acquisition' action stage.

Interestingly, medium MLOA was assessed at 'Level 5' only at the 'Information acquisition' action stage at the Radiation oncologist, Medical physicist #1, and Anaesthetist. Radiation oncologist's 'Level 5' 'MLOA' was at the following operations which required more automation for data acquisition, and less automation when for information analysis, decision selection, and decision making: "Volume post needle", "Virtual prostate and urethra positioning", "Peripheral seeding and planning, and "Central seeding and planning". For the Medical physicist #1, this was at the following operations: "Peripheral plan verification", "Estimate central needle positioning and seed implantation", and "Final verification (dosimetry). For the Anaesthetist this was at "Patient monitoring" operation. The other three MLOA action stages for the operations just mentioned above were assessed at 'Level 2'. This means that in the present system, the automation acquires the information and presents it to the human operator, and at the same time the MLOA of the other three actions stages are predominantly performed by the human operator, with very limited options provided by automation.

Future systems

- Gradual progression: It is important to emphasise that the change of LOA will not be immediate, but a gradual progression. It may take years by the time the operators, that is the core team members, to accept the ongoing development of the technology, trusting the automation, as well as the reliability and performance of the equipment. Introducing new technologies may require change of the amount (or order) of operations and sub-operations, that the core team members are performing in the present system, or even change in staffing levels. Such changes take time, change of habits, roles, responsibilities, upgrading skills, knowledge, etc. The gradual progression of the future brachytherapy system was well presented in the conference paper by Fallon et al. (2015) where the authors compared the 'Current Automation Scenario', 'Mixed Automation Scenario', and the 'Future Automation Scenario'. The gradual progression from the current scenario will change slightly to 'Level 6' LOA at the "Information acquisition" stage, to 'Level 5' LOA at the "Information analysis" stage and "Decision selection" stage, and to 'Level 8' at the "Action implementation" stage. These predictions mostly match the 'preferred LOA' researched in this thesis, which indicates that from the human operator's standpoint, the LOA will progress to 'Level 8' LOA at the "Information acquisition" stage, to 'Level 8' LOA at the "Information processing" stage, whereas only to 'Level 3' LOA at "Decision selection" and "Action implementation" stages. It is almost impossible to predict exactly how the gradual progression will go, but we can expect higher LOA especially at the "Information analysis", "Decision selection" and "Action implementation" stages. This means the information will be analysed much faster, and the operators will get more help with the decision making and action implementation. This may mean drastic changes of the operations and sub-operations, and consequently, also changes in perceived workload levels as well as TLX dimension(s), especially changes in MD, PD, TD and EF. It is unclear exactly how the levels of perceived workload will change in the future, but they might increase with higher LOA, rather than decrease (Wickens, Li et al. 2010).

- The changes in the LDR prostate brachytherapy core team: Some core team members will perform different or less operations and sub-operations in the future compared to the present system, and therefore their roles and responsibilities will change. With increased LOA, the number of core team members may reduce. Most of the operations performed by the Nurse and Medical physicist #2 in the present system may be automated in future systems, and there may be no need to perform all operations identified in the present system. E.g., the Nurse may only perform the "Patient setup" operation, and Medical physicist #2 may only focus on the "QA of the source activity", as there would be no need to perform other operations due to high (or full) levels of automation. The changes in the core team member numbers may help with staffing shortage, as the core team members' skills and knowledge might be needed elsewhere.
- Supervisory role: Despite partial or full automation being developed at present, and being introduced in the future, the role of the human operator will become more supervisory. For example, the role of Radiation oncologist and Radiologist (where applicable) at the "Treatment delivery" stage may change by introducing advanced decision making in order to ensure a safe and effective treatment performance. The role of Medical physicists may change into decision making and supervising multiple virtual models and isodosis. Their supervisory role would change in the cases of emergency (that is in cases of when patient safety is compromised due to automation failure), when the LOA would switch from a highly (or fully) automated level to a less

automated (or manual) level. Therefore, even with the "fully" automated system, the LOA should remain at "Level 10a" of the 'MLOA' model, where the human operator still has the ability to veto the computer's actions in order not to compromise patient's safety, because in the case of automation failure, the effect on the "human-machine" system could be catastrophic (Wickens, Li et al. 2010). The automation design would need to accommodate appropriate 'optimal level' levels of perceived workload of the Radiation oncologist's and Radiologist's mental and physical capabilities to successfully match or adapt to the changes in LOA in such case.

- Training: with more advanced systems and higher automation, the need for additional and more specialist training may increase in the future. More time may be needed to operate highly automated equipment in different LOA scenarios, e.g. in a "fully" automated scenario, a "manual" LOA scenario, emergency cases, etc. This may include training in hardware and software every time the technology advances or changes. Training should be designed to be cost effective for the hospital and to upgrade core team member's roles and responsibilities.
- Cost effectiveness: Higher automation may contribute to less core team members being present at the 'Treatment delivery' stage of LDR prostate brachytherapy treatment. On one hand, the cost of equipment would be higher. On the other hand, the highly automated equipment would be more efficient and could reduce treatment time; therefore the hospital could offer more LDR prostate brachytherapy treatments during the same time slot. For example, if the hospital performs two 90 minute LDR prostate brachytherapy treatments a day, they could, potentially, if the technology/equipment allowed, reduce the treatment time to 60 minutes per treatment, and perform three, and not two treatments in the same time slot, which would benefit the hospital's budget, and help with the return on investment into the technology. This could in return increase the number of patients treated, and consequently it would also mean shortening the patient waiting times.
- Combined technologies: a combination of "loose" seeds and "stranded" seeds LDR prostate brachytherapy has already been introduced to the present market. It is reported that this combined technique reduced the treatment time

by 50% (4D Brachytherapy 2015). However, at this stage it is just a matter of time to see the birth of more advanced technology that would make LDR prostate brachytherapy even more efficient. With a slight speculation it can be concluded that the development of the advanced technology will include an improved prostate imaging system in some sort of a combination of MRI and CT technology, high-density 3D or 4D ultrasound technology, radio frequencies, improved or redesigned electronic seed delivery devices, e.g. improved Mick® applicator system with a larger interconnected seed cartridge and more efficient seed delivery system with a digital counter, as well as advanced outputs of the 3D prostate imaging, combined with real-time imaging and advanced 4D seed implantation models which will include extraordinary complex software treatment model simulations during the real-time seed implantation to target the optimal isodosis, etc.

It is important to state that the future technologies will completely change today's LDR prostate brachytherapy user-system setup. It must also be emphasised that besides increased efficiency and high(er) automation, the design should allow for optimal workload levels of the core team members, an exceptionally safe treatment with an exceptionally high level of patient safety.

These guidelines researched the fifth and final research question: "How will the perceived workload relate to the 'Modified Levels of Automation' in the future Low-Dose Rate prostate brachytherapy system?"

8.3 Chapter summary

This chapter provided a general discussion to this research focussing on the guidelines and recommendations of the application of perceived workload and 'Levels of automation' to the present and future LDR prostate brachytherapy systems, written from the human-centred Human Factors Engineering perspective. The guidelines and recommendations for the present system included the technologies used in the LDR prostate brachytherapy treatment (e.g. the stepper, cartridge, Mick® applicator, etc.), and 'Levels of Automation'. The guidelines and recommendations for future systems anticipated gradual progression, changes within the core team, changes in terms of operations and sub-operations (including reduction of some operations), moving towards the supervisory role, combined techniques, etc. These guidelines and recommendations further researched the fifth and final research question on the topic of relation of perceived workload and 'Modified Levels of Automation' in the future systems. The next chapter will provide conclusions to this research study.

Chapter 9: Conclusions

9.1 Chapter overview

This final chapter provides research summary and conclusions, outlines its contribution to knowledge, provides limitations to this research, and outlines the future research challenges.

9.2 Research summary and conclusions

HTA was developed during the thirty two LDR prostate brachytherapy treatment cases. The main operations and sub-operations were identified among the core team members at the "Treatment delivery" stage of the "loose seeds" and "stranded seeds" LDR prostate brachytherapy: Radiation oncologists, Radiologists (where applicable), Medical physics team, Nurses, and Anaesthetists. The main operations identified served as a basis for the assessment of perceived workload and application of the 'Modified Levels of Automation' (MLOA) model for brachytherapy. Perceived workload was assessed at forty eight treatment cases by using a NASA-TLX method (Hart and Staveland 1988). NASA-TLX method included the application of the 'TLX worksheets' to each of the main core team members' operations at the 'Treatment delivery' stage of the LDR prostate brachytherapy treatment across four hospital sites in Ireland. Each TLX worksheet consisted of assessing the workload level (resulting in a TLX score), and a pair-wise comparison table (resulting in the overall TLX dimension proportions) of six dimensions: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration (Hart and Staveland 1988). TLX data was collected and analysed from 1073 TLX administered worksheets for each core team member across each hospital site separately. After that, the 'Revised workload rating scale' was applied to the TLX scores to determine the potential workload red-line values which may compromise patient safety. No safety critical workload levels were identified despite low workload levels found among Radiation oncologists, and high workload levels found among Medical physicists, Nurses, and Anaesthetists. The main three predominant TLX dimensions were "Mental Demand", "Temporal Demand" and "Effort". Automation and LOA models were researched to model an appropriate LOA model for brachytherapy/radiotherapy. A MLOA model was developed based on the previous models by Parasuraman et al. (2000) and Sheridan (1997), and applied to identify the current state of the LDR prostate brachytherapy LOA system. The modification of MLOA focussed on determining the high LOA, where the human operator would still have the control over the automation, and would be able to veto the machine(s), meaning, the automation would switch from higher LOA to medium LOA in order to preserve patient safety. The benefits of the higher LOA may include more efficient treatment, changes in the roles and responsibilities of the core team members, change of the staffing levels, and also switching of the main human operator's role into a more supervisory role. Furthermore, the human-automation questionnaire researched automation-related topics, such as trust in automation, reliance on automation, perceived reliability of automation, and 'preferred' LOA among the core team members who were predominantly involved with automation and automated systems during the 'Treatment delivery' stage of the LDR prostate brachytherapy system, including Radiation oncologists, Radiologists (where applicable) and Medical physicists. The questionnaire revealed that the core team members trusted the automation/technology in the present system, in particular the TRUS feedback and computer screen output, which are one of the most crucial elements of the treatment delivery, besides Mick® applicator. This was also confirmed with a high reliance on the TRUS feedback and visual output(s), because these are crucial for team decision making on treatment planning and treatment delivery. The core team members also reported that the equipment they use is occasionally faulty, and that further automation of this equipment would improve the quality of the brachytherapy delivery. There was some fear present about the impact partial or full automation would have on their performance especially because of the impact the higher automation could have on the roles and responsibilities and the staffing levels within the team. In the future, the 'preferred LOA' identified the two most likely LOA action stages that are going to change first; they are the "Information acquisition" action stage and the "Information analysis" action stage. The investigation of the relationship between 'Perceived workload' and 'MLOA' involved a number of statistical analyses methods, including Pearson's Correlation Coefficient, ANOVA, T-test, Linear and Non-Linear Regression. It identified a moderate or high correlation between 'Perceived workload' and 'MLOA' action stages among Radiation oncologists, Radiologists (where applicable), Medical physicists, Nurses, and Anaesthetists. It identified and confirmed that there *is* some correlation between the levels of perceived workload and 'LOA' action stages in the present LDR prostate brachytherapy system. The future guidelines and recommendations of the future LDR prostate brachytherapy human-automation systems suggest a gradual development and introduction of higher LOA to accommodate the changes in the number of the core team members' operations, in particular for Nurses and Medical physicists with increased LOA over time. Higher LOA will most likely change core team members' roles into supervisory roles, and will require specific training while keeping the optimal workload levels, and providing an exceptionally high level of patient safety. The development of the future LDR prostate brachytherapy automated systems is exciting, and should include the principles highlighted in this thesis, such as the levels of perceived workload and the tools that identify critical levels of workload, the application of 'MLOA', the ability to switch from a fully automated system back into a lower automated system, being aware of the human-automation issues, such as trust in automation, perceived reliability of the system, as well as changes in staffing levels, the levels and the amount of additional specific training to enable safe and efficient LDR prostate brachytherapy treatment.

9.3 Contribution to knowledge

This research has made the following significant contribution to knowledge:

i. The study performed for this thesis is one of the first research studies on the topics of perceived workload, automation, and automation-related issues in Low-Dose Rate brachytherapy. Such research has not been performed before, especially to this extent, and in the clinical healthcare environment.

ii. The three main topics were studied carefully and extensively, and are presented in the literature review. The most appropriate and applicable methods and techniques that were selected and used in this research were the NASA-TLX method and Hierarchical Task Analysis.

iii. A 'MLOA' model is a good example of 'known' LOA material which had to be modified to fit a specific working environment.

iv. Due to the lack of suitable existing methods, new tools and methods had to be developed, e.g. the ‘Revised workload rating scale’, and a ‘Modified Levels of Automation’ model.

v. A set of new workable tools for use within a Radiotherapy Department was developed. These tools are also transferable to other areas of healthcare, where highly automated equipment is used:

- The ‘Revised workload rating scale’
- The guidelines on red-line values
- The ‘Modified Level of Automation’ model for radiotherapy/brachytherapy
- Guidelines and recommendations for present and future brachytherapy systems

vi. Once the topics of cancer, radiotherapy and brachytherapy were studied, the LDR prostate brachytherapy was extensively mapped. Perceived workload was assessed using the NASA-TLX method over four hospital sites in Ireland, which was the first case study on this topic in Ireland. The analysis of TLX workload scores was critically approached, and compared with the ‘Modified Levels of Automation’ model, also specifically developed to fit this research domain. As a result, new tools were developed, and new guidelines and recommendations were given. Critical thought is also presented in the Discussion chapter of this thesis, where a good knowledge of the present LDR prostate brachytherapy treatment process was merged with the Safety and Human Factors Engineering principles.

vii. The topics researched in this thesis had to be approached from an engineering perspective. It required an extensive learning curve not only to become familiar with the healthcare environment, but also to become familiar with the specific procedures and operations of this highly controlled and highly regulated environment. Nevertheless, it was easier to identify the gap from the ‘outside’, from an engineering perspective, and to apply it to the ‘inside’, to the healthcare environment.

viii. Parts of this research have been published on ongoing basis in conference proceedings, posters, and abstracts. The collected data presented in this thesis can be published further in journal papers, books, or as book chapters.

9.4 Research limitations

The biggest limitation was a limited number of sites which perform LDR prostate brachytherapy in Ireland. The data was collected only from four hospital sites. If the data was collected elsewhere, e.g. in the UK, where they have over 20 LDR prostate brachytherapy centres, a larger number of sites could be included in the research.

Analysing the NASA-TLX data was time consuming due to a high volume of the returned TLX worksheets. The data collection and analysis may be quickened by using an electronic TLX worksheet on a tablet, which would analyse the data straight away, and would have an ability of exporting it to a database. However, a number of reliable tablet computers would be needed for each core team member, which may increase research costs.

No data was collected on physiological workload in this research study, e.g. heart rate, blood pressure, brain activity, eye blinks, eye positions and movements, due to the clinical environment, limited time availability, time pressure, the core team members wearing the protective clothing, e.g. gown, gloves, etc. Collecting physiological data might make the perceived workload data more comparable in terms of applied research, e.g. when using TRUS/ultrasound, or when using the computer software/hardware. It may also require additional resources in terms of buying appropriate equipment for the whole core team.

Only a single observer was used to collect data: observational and collected data may have had an even better response rate if more than one observer was present in the clinical environment during this research. However, having an additional observer present at any of the other different hospital sites would have been more expensive, it would mean a physical space issue due to limited space available at some of the sites, and may make core team members uncomfortable with an additional person present at the site. This, however, could be solved with clear roles of the researchers, e.g. what kind of data would each researcher be collecting and how the data would be collected.

9.5 Future research

The future research on perceived workload might include a combination of objective and subjective workload methods and consequently a more complex data acquisition, e.g. collecting data on heart rate, skin temperature, eye blinks, eye positions and movements, blood velocity, brain activity in parallel to using the subjective rating scale, e.g. NASA-TLX, make it fit into the radiotherapy/brachytherapy environment. For example, Mazur et al. (2013) were assessing subjective and objective workload of the Radiation oncology physicians during EBRT planning tasks in a controlled, simulated environment. NASA-TLX was used for subjective measurement, while pupil size and blink rate were used for objective measurement. The correlation between subjective and objective workload was assessed via the Pearson's Coefficient test. There was some correlation between the perceived workload and the average blink rate, but no correlation between the perceived workload and the average pupil diameter. They concluded that subjective and objective workload measures do not necessarily track each other (Mazur, Mosaly et al. 2013). In other industries, Borghini et al. (2014) were researching how the pilot/driver's brain activity performs during driving performance, and how can this be connected to the particular brain activity in terms of mental workload, mental fatigue or situational awareness. They concluded that particular EEG rhythms may be indicators of mental activity "related to overt driving performances and/or to the occurrence of errors" (Borghini, Astolfi et al. 2014), and that the accuracy of detection of the mental stress in drivers/pilots using EEG, Heart Rate, etc., is highly accurate. They concluded that there is a need to generate a good and well controlled EEG dataset related to the occurrence of the mental workload corresponding to different mental states (Borghini, Astolfi et al. 2014). The same would also apply to the creation of such datasets in the area of healthcare, and in particular, to radiotherapy, and LDR prostate brachytherapy, especially because the EEG equipment itself is fairly inexpensive, and easy to apply, but would require using very specific methodologies of data collection, extensive knowledge of brain biometrics, expertise on local brain regions, knowledge of EEG brain rhythms, data acquisition protocols, etc. Amin et al. (2014) performed a study of mental workload of nurses in a hospital by continuously monitoring their brain activity for the entire duration of the 12-hour shift. The results reported that EEG “may be sensitive to measure mental demands imposed on nurses while performing their daily routine activities in a hospital unit” (Amin, Fredericks et al. 2014). This means that EEG may be a useful method for collecting objective workload data in the future in the healthcare environment. In a separate study, Ayaz et al. (2010) used a different device, called the fNIR, which measures cerebral hemodynamic response by using near infra-red light, similar to fMRI, and NASA-TLX, to assess the standardised and complex cognitive tasks during two different flight simulator experiments in a controlled, simulated environment: the first experiment had 24 Air Traffic Controllers, and the second experiment had 7 college students. The results of the first experiment reported a strong brain activity in specific brain regions, corresponding to different task scenarios, and different responses between experienced and novice Air Traffic Controllers. The results of the second experiment reported reduced neural activation of the specific brain area (Ayaz, Willems et al. 2010). Unfortunately the authors did not provide a data comparison between the assessed fNRI data and NASA-TLX data. Similar to EEG, fNIR is a small, non-intrusive portable device, which can be useful for the data collection in critical multitasking environments. However, similar to the EEG, it requires a specific knowledge of how to use the device, how to correctly and accurately collect the data, and nevertheless, how to compare and relate this data to a subjective perceived workload assessment, assessed for example, with NASA-TLX. The data will have to be collected very carefully, and similarly to the EEG data, fed into a healthcare-specific database, which would contribute to the future research.

Since it may be easier to collect the data in a controlled experimental healthcare setup, with medical students and training staff, it is highly recommended that for optimal results, such data is collected in a clinical environment, like in our study, with experienced core team members performing their operations in real time. This would impose additional challenges in data collection, especially when asking the core team members to commit towards wearing the EEG device or fNIR device during the LDR prostate brachytherapy treatment for objective data, filling out the

NASA-TLX worksheets for subjective data, and/or having additional eye/pupil tracking devices present in the operating theatre. It would most probably also require one or more additional researchers being present during the treatment, which may consequently limit the already limited space in some operating theatres.

The future research may also look into developing a specific toolkit for easier workload assessment of the core team members which would not be focussing on the patient-related workload, but more specifically on the core team members' operations, e.g. an expanded or redesigned NASA-TLX tool in terms of additional dimensions, moving from a pen and paper based approach into something more interactive. Another alternative may be to combine the NASA-TLX assessments with the assessed team workload, with the tools like Observational Teamwork Assessment for Surgery (OTAS) or Team Workload Assessment (TWA). The OTAS tool assesses teamwork of the entire team in the operating room assessing 5 different behaviours through direct real-time observations of 5 behaviours and examplar consensus consisting of 130 examplars (behavioural traits) in the form of a list: communication, leadership, cooperation, coordination, and team monitoring). It has demonstrated a very good content validity (Hull, Arora et al. 2011). It has been applied to the urological surgery (Undre, Sevdalis et al. 2007), and general surgery in the operating rooms (Hull, Arora et al. 2011). The only downside it that it requires at least two researchers to be present in the same room as the core team members. The TWA tool which was developed to assess the team workload by teamwork characteristics, developed by Lin et al. (2011) for the nuclear industry. The researchers reported that the team workload scores assessed with the TWA were more sensitive to task performance than those assessed directly with the NASA-TLX (Lin, Hsieh et al. 2011). It would be interesting to see the applicability of the OTAS and/or TWA tools to the radiotherapy and the LDR prostate brachytherapy environment.

Another area the future research may look into is the correlation between the perceived workload and errors in LDR prostate brachytherapy. For example, Mazur et al. (2014) were researching the relationship between the perceived workload and errors during the EBRT planning stage in a laboratory simulation-based setting. The perceived workload was assessed with NASA-TLX, while the errors were assessed with direct observation of the subjects by 2 researchers using an external camera and video capturing software. Each error captured has been assigned a grade, based on the “severity grade of errors” (grade classes were between 0 and 5). The results have shown that most of the higher levels of perceived workload correlated with the error grade 1 or 2 (grade 1 was classified as a ‘Mild’ error, while grade 2 was classified as a ‘Moderate’ error) (Mazur, Mosaly et al. 2014). Their error assessment was based on the observational study, which would work better in a closed, simulated environment, but would be more challenging in the real clinical environment because it would have the whole core team present, as well as the patient. It would also require capturing and recording audio and video during the treatment, which would be very time consuming, because the researchers would need to analyse hours and hours of footage independently in order to extract solid data.

The future research may also look into detailed investigation of the relationship between automation and LOA when new technologies are introduced, when operations and sub-operations change, or when a number of core team members change. Any slight change might have an impact on the subjective and objective workload, and unless it is assessed regularly (for example 1-2 times per year), it is almost impossible to track the changes and to see the impact of those changes.
In the future it would also be interesting to see a further application of the ‘Revised workload rating scale’, the application of the “red-line” levels, and the application of the ‘Modified Levels of Automation model’ to radiotherapy, LDR prostate brachytherapy, and to other safety critical industries. Such application could result in a wide data collection at national and international level, which could potentially lead to a creation of a database that would serve as a main source for such data. The database would serve as a guideline for improving the radiotherapy/LDR prostate brachytherapy evaluation of the existing technologies, or as a guideline for developing brand new or existing technologies. It could also serve as a think tank for new ideas, and how to successfully integrate them into the gradual advancement of the technology, until in the distant future, all, or most present operations and sub-operations become partly- or fully- automated, and the role of the human operator evolves into a supervisory role of the user-system automation.

9.6 Chapter summary

This final chapter provided research summary and conclusions, outlined its contribution to knowledge, provided limitations to this research, and outlined the future research challenges.

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