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THE DEVELOPMENT OF A MOBILE APPLICATION TO ENHANCE FETAL RADIATION DOSE MONITORING AMONG PREGNANT RADIOGRAPHERS.

by

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Dedication

This dissertation emerged from the birth of my children and ended with the passing of my mother.

Therefore, I dedicate this work to my daughters, Nurah Imaan and Amaanah, who led me to the research problem and inspired the mobile application. I hope this tribute inspires you to pursue your dreams like you did for me.

I also dedicate this work to my father, Sayeed Rahman and my late mother, Zenath Yanum Rahman, who never graduated yet instilled the value and importance of education in me. All the sweat of your hard work and sacrifices for me translated into this pinnacle of my life. To my mom, I know you will be looking down from heaven with pride as I cross the stage.

To my husband, Mika'il Essop, your sacrifices enabled my academic career. Words cannot thank you enough for flying across the world with me during this research journey and always supporting me.

Lastly, I dedicate this work to all the vulnerable pregnant radiographers of South Africa; I hope this research serves as your voice and continues to support you and the next generation of pregnant radiographers.

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Declaration of Authorship

I, Hafsa Essop, declare that the research study:

The development of a mobile application to enhance fetal radiation dose monitoring among pregnant radiographers

which is submitted in accordance with the requirements for the PhD (Radiography) degree at the University of Pretoria, is my original work and has not previously been submitted to any other institution of higher learning. All sources cited or quoted in this research paper are indicated and acknowledged with a comprehensive list of references.

Mrs H. Essop

15th April 2024

Declaration of Publications and Manuscripts

The following articles and manuscripts contribute to Chapters 3 to 5 of this dissertation. Table 1 outlines the status of each and the journal or conference proceeding to which it has been submitted.

Table 1: Summary of articles and manuscripts related to each chapter.

Contributing chapter	**Article/Manuscript/Conference Proceeding**	**Journal and Status**	**Proof of submission**
Chapter 3	1. Essop, H, Kekana M, Smuts H, Masenge A. Fetal dosimeter access, usage and training among pregnant radiographers in South Africa. J. Radiol. Nurs. 2023; Vol 42 (4).	**Published** Mobile application https://www.youtube.com/watch?v=o_UeJdYqUOE	Appendix A
Chapter 4	2. Essop, H, Kekana M, Smuts, H. PregiDose: A mobile application designed through a user-centered approach, to enhance fetal dosimetry and wellbeing among pregnant radiographers.	**Abstract published:** *Annals of the ICRP* abstract book Short paper - In review, Conference proceeding	Appendix B
	3. Essop, H, Kekana M, Smuts, H. Co-Designing of a mobile application to enhance fetal dosimetry and well-being among pregnant radiographers: a design thinking approach.	J.Health Inform. – **In review**	Appendix C
	4. Essop, H, J Brosens, Kekana M, Smuts H. Implementation of a mobile application developmental model towards PregiDose. A mobile application for pregnant radiographers.	J. Med. Internet Res. (*JMIR*) Research protocols **– In review**	Appendix D
Chapter 5	5. Essop, H, Kekana M, Smuts, H. Perceptions of pregnant radiographers regarding the usefulness and usability of PregiDose. A mobile application to enhance fetal dosimetry and well-being.	to Int. J. Med. Inform. **– In review**	Appendix E

Executive Summary

Introduction: Ionising radiation has the potential to have harmful effects on cells. The risk of these effects increases in a fetus whose tissues are still developing. The effects of radiation, which depend on the amount of exposure received, can present as deterministic or stochastic effects. Based on this theory, occupational health and safety are heightened for the pregnant radiographer who is required to wear a special dosimeter to record and monitor the fetal dose exposure. This process is self-regulated by the pregnant radiographer. In the clinical department, it was observed that pregnant radiographers have inconsistent methods of recording and monitoring their fetal dose. Therefore, the study aimed to develop a mobile application to support and enhance fetal dosimetry among pregnant radiographers.

Methods: The research followed a design science research (DSR) paradigm and the behaviour change, user-centred and social marketing (BUS) framework, which guided the objectives of this study. The study adopted a mixed methods research design, incorporating five major phases, aligned with the DSR paradigm, namely 1) Problem Awareness, 2) Suggestion, 3) Development, 4) Evaluation and 5) Conclusion. In Problem Awareness, the reviewed literature highlighted the problem as it exists in the literature as well as a situational analysis into the problem as it exists in the context of this study. In the Suggestion phase, recommendations are made towards addressing the problems identified in literature and the situational analysis. In the Development phase, two cycles took place. Firstly, prototype design, which adopted a design thinking methodology. Secondly, the Mobile App Development Lifecycle (MADL) to develop and test the final app. In the Evaluation phase, pregnant radiographers engaged with the app in the real-life setting. Qualitative interviews were then conducted to ascertain the usability and usefulness of the app.

Results: In DSR Step 1, the study identified a lack of literature regarding pregnant radiographer compliance towards fetal dosimetry, presenting a gap in the literature. The problem awareness through the situational analysis revealed inconsistent fetal dose recording and monitoring. The study concluded that pregnant radiographers needed support regarding fetal dosimetry. This suggestion is a mobile application encompassing core functional areas such as dose tracking and education to address some of these challenges. In DSR Step 3, the prototype was designed by its actual users, who named the app *PregiDose*. The users further uncovered that pregnant radiographers suffer from decreased emotional well-being in the clinical setting and required support. The final app was then developed in collaboration with software engineers. In DSR Step 4, the pregnant radiographers who had been interviewed after engaging with the app revealed that it was both easy to use (usability) and useful. However, they recommended automation, whereby the doses from the dosimeter could be linked to the app automatically.

Conclusion: DSR Step 5 corresponds to the conclusion of the research process. The study has highlighted that a mobile application for pregnant radiographers can enhance fetal dose monitoring. The research made the following contributions: first, to the field of research by describing the rigorous process of development and evaluation, and second, to the field of radiography and radiation protection, demonstrating that technology can be used to facilitate occupational health and safety and, in line with the pragmatic nature of the DSR paradigm, solve a real-life problem.

Key words: Fetal dosimetry, pregnant radiographer, mHealth, radiation protection, mobile application, Design Science Research, Design thinking, mobile app development lifecycle, usability, usefulness,

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CONCEPT CLARIFICATION

The following terms are used throughout this document and pertain to the study and its context.

Table 2: Definition of Key Terms

Term	Definition
Radiation worker	An individual who deals with equipment or substances that emit ionising radiation as a result of their occupation that produces more or equal to 20 mSv per annum.[1]
Radiation dose	X-ray energy has the potential to cause harm if absorbed by tissue. Radiation dose is measured in millisieverts and miligray (mGg), often used interchangeably. Millisieverts (mSv) express the absorbed dose of the entire body and milligray takes into consideration the sensitivity of different organs.[2]

Dosimeter	A dosimeter is a monitoring device that measures the quantity of radiation the radiation worker may be exposed to in their working environment.[3] There are several types of dosimeters, such as film badges, thermoluminescence dosimeter and direct reading pocket alarms dosimeters.
Thermoluminescent Dosimeter	This dosimeter contains small chips of thermoluminescent material. Doses are measured by placing the dosimeter in a reader and the amount of released visible light is equivalent to the absorbed radiation dose. It is small in size and is often used for measure exposure to the extremities such as the hand in the form a ring[3].
Direct Reading Pocket Alarm Dosimeter (DRPAD)	DRPAD is a dosimeter that measures the quantity of exposure it has received[3]. It immediate reading and can detect doses of up to 0.02 msv. It has a built-in alarm that can be programmed to ring when the desired threshold radiation dose is reached.[3] This type of dosimeter is recommended for pregnant radiographers in SA by SAHPRA. The disadvantage of this dosimeter is that it can produce false readings and does not provide a permanent record.[3] For this reason, radiographers are expected to keep a manual record of their doses.
Mobile application	A software application developed specifically for use on small, wireless computing devices, such as smartphones, using software programmed into a smartphone, aiming to monitor and record a particular activity closely by enabling the user to input, retain and retrieve data in a single, convenient space.[4]

ABBREVIATIONS

Table 3: List of Abbreviations

Abbreviation	Terminology
BUS	Behavioural, User-Centred, Social Marketing
DSR	Design Science Research
DRPAD	Direct Reading Pocket Alarm Dosimeter
HPCSA	Health Professionals Council of South Africa
ICRP	International Council of Radiation Protection
MADL	Mobile Application Design Lifecycle
mGy	milligray
mSv	millisieverts
NRC	Nuclear Regulatory Council
OHS	Occupational Health and Safety
PRMD	Personal Radiation Monitoring Device

SABS	South African Beuro of Standards
SAHPRA	South African Health Products Regulatory Authority
SDG	Sustainable Development Goals
TAM	Technology Acceptance Model
TLD	Thermoluminescent Dosimeter

CHAPTER 1: INTRODUCTION

"*We have the duty to protect the life of an unborn child*" Ronald Reagan

1.1 Introduction

Dosimetry among the general population of radiographers in the context of radiation protection has been well explored[5]. Technological advancements in dosimetry include real time dosimetry through mobile app technology which has the ability record and monitor radiation doses[6]. These advancements have been in the context radiation accidents[6], however its exploration in the context of occupational health and safety has been limited.

Pregnant female radiographers are considered a vulnerable population of radiographers, who require stringent and highly sensitive dose monitoring in comparison to general practising radiographers[7]. The prescribed occupational dose limit for a practising radiographer is 20 milliSieverts (mSv) per annum. This must be monitored through a personal radiation monitoring device (PRMD), also known as a dosimeter. This device is sent to a service provider, which measures the monthly doses and generates a radiation dose report for the user.

The radiation control division of the South African Health Products Regulatory Authority (SAHPRA) states that all radiation workers in South Africa must wear Thermoluminescent Dosimeters (TLD) in the form of clip-on badges.[3] However due to the sensitivity of the unborn fetus, the radiation dose limit for a pregnant radiographer is limited to 2 mSv for the entire duration of the pregnancy.[3] Thus, pregnant radiographers are required to use two dosimeters, one for themselves and a second dosimeter to monitor radiation doses to the fetus.[3]

Critical organs and body structures form in the embryonic developmental stage of a fetus.[8] When radiation interacts with these developing cells, there is a potential for the fetus to be born with congenital malformations or genetic disorders, which can, in turn, be passed onto their offspring.[2] Fetal dosimeters, such as Direct Reading Pocket Alarm Dosimeters (DRPAD) or electronic personal dosimeters, provide real-time dose readings, which require more stringent monitoring, whereby the radiation doses indicated on the device must be recorded daily by the pregnant radiographer.

Several studies have investigated radiographers' compliance with wearing dosimeters. A study by Abuzaid et al.[5] investigated the adherence to radiation safety practices among radiographers and identified that only 62.5% of radiographers used dosimeters at work, with 15.7% never wearing them.[5] In South Africa, Modiba[6] investigated the compliance of radiographers towards radiation dose monitoring. Results from this study revealed that only 59% always use their dosimeters.[6] Modiba[6] explains that noncompliance is unacceptable and against the regulations; it also wastes valuable resources and increases health risks. Selemela[7] finds similar results regarding non-compliance with dosimeter usage, with only 56% of radiographers wearing their dosimeters during a spot check in four academic hospitals in Gauteng.[7] In 2020, Karellas,[8] the Director of Biomedical Innovation at the University of Arizona, concurred with these findings and stated that inconsistent usage of the dosimeter and dose recordings might interfere with the accuracy of the dosimetry and the analysis process.[8] Based on these findings, it is evident that dosimeter usage among radiographers is not consistent. However, it is unknown if pregnant radiographers are indeed compliant with wearing fetal dosimeters and recording the daily doses derived from them, which is an added responsibility.

These uncertainties created the first identified insufficiency in the literature, which forms part of the first objective of the current study: To perform a situational analysis of the methods of fetal dose recording and monitoring among pregnant radiographers in South Africa. In 2003, Singh[9] recommended recording fetal doses in a log book and providing copies to the radiation protection officer monthly. However, in the current technological era, there is a rapid move away from paper-based recording to electronic record-keeping. This is especially evident in monitoring health and wellness being facilitated through mobile applications, which enables effective and consistent recording and tracking of any input in a smartphone directed at a specific healthcare goal.[10]

Mobile application usage among pregnant women is on the rise, with women using these applications to seek more information, track individual health indicators, and monitor fetal development and movement frequency to provide reassurance.[11] Pregnant female radiographers who are at risk of occupational radiation exposure not only have to be cognisant of the above-mentioned factors associated with pregnancy but must also be aware of occupational radiation dosage to themselves and their fetuses. This provides a rationale towards the adoption of advances in technology towards supporting fetal dosimetry. The aim of the study was therefore to develop a mobile application to enhance fetal dose monitoring.

1.2 Thesis Background

In South Africa, radiation safety is regulated by SAHPRA, derived from the ICRP publication 84.[12,13] The implementation policy pertaining to the radiation monitoring of a pregnant radiographer, posted in January 2015, states the following[3]:

a. Equivalent dose to the pregnant female radiographer’s abdomen may not exceed 2 mSv for the remainder of the pregnancy.

b. Once pregnancy is confirmed the radiographer must inform the employer.

c. The employer must carefully review exposure conditions to ensure radiation exposure does not exceed the prescribed dose limit.

d. Pregnant radiographers must be issued a direct reading audible dosimeter, also known as a direct reading pocket alarm dosimeter (DRPAD).

Although the SAHPRA guidelines have been adopted from the IRCP 84 legislation focusing on pregnancy and radiation, neither radiation protection bodies guide the method of record-keeping radiation doses from the DRPAD, which is self-monitored, unlike the TLDs, which are monitored monthly by the South African Bureau of Standards (SABS). The Nuclear Regulatory Commission (NRC) standards for radiation protection also raised this concern and proposed implementing more stringent monitoring regarding fetal doses.[14] However, the researcher could not find a record of any amendment to these regulations. Accordingly, the researcher assumes that the method of dose monitoring is at the discretion of the pregnant radiographer and, thus, can occur in any form, such as manually recording daily doses in a logbook, as suggested by Singh,[9] using the software provided by the service provider which utilises a CD and computer, if available to the radiographer or in an electronic memo on the radiographer's smartphone. The implication of this might lead to inconsistencies in the proper self-monitoring of doses, whereby radiation exposure to the radiographer's abdomen could possibly exceed the stipulated 2 mSv fetal dose throughout the pregnancy.

The researcher is a qualified radiographer with more than five years of clinical experience prior to joining the academic environment. The researcher is also involved in the supervision of radiography students in the clinical setting. While conducting her duties, she observed the following regarding pregnant radiographers and dosimetry.

- Some pregnant radiographers did not always wear the DRPAD device as prescribed by SAHPRA. Those wearing it seemed to have been using it incorrectly in terms of its placement.
- Some pregnant radiographers did not record their daily readings and, therefore, did not have monthly recordings.
- The service provider provided some radiographers with software on a CD, which could be uploaded to a computer to record readings from the service provider. The computers available in the department were often in the reception area and chief radiographer's office, thereby compromising the confidentiality of the readings and limiting radiographers' daily access to the computers to upload readings.

Based on these observations, the researcher assumed pregnant radiographers were not fully compliant with dosimeter usage. The researcher further assumed pregnant radiographers might have inconsistent dose recording methods. This study validated these assumptions through a situational analysis to confirm such methods of fetal dose recording and monitoring. Radiographers who had either been pregnant in the past or were currently pregnant were invited to participate in this situational analysis. The findings of the analysis confirmed the need for a further support mechanism, called for the development of a mobile application. The mobile application was developed through a rigorous process under the DSR research paradigm and elaborated on Manuscripts 3 and 4 in Chapter 4.

1.3 Problem Statement

Research problems identify an area of concern and provide reasons why the issue should be explored.[15] In this study, areas of concern emanated from the pregnancy regulation guidelines, anecdotal experiences from the researcher and pregnant radiographers, the reviewed literature, and unmet market demand for supporting technology.

Under the SAHPRA guidelines, it is assumed that fetal dose monitoring is at the discretion of the pregnant radiographer, who must independently record and monitor the fetal dose from the supplied DRPAD, unlike pregnant radiographers in, for example, Nebraska, who receive training on dosimeter placement, usage and recording.[16] If this is not performed consistently and accurately, it could potentially harm the pregnant radiographer and fetus, as they might be exposed to radiation doses that exceed their threshold limits and thus contribute to stochastic radiation effects. Inconsistent record-keeping of the fetal dose also contravenes medicolegal requirements of the three-year time frame required for keeping records, as well as the Occupational Health and Safety (OHS) Act, No 85 of South Africa. The OHS Act states: “No person shall intentionally or recklessly misuse anything which is produced in the interest of health and safety”.[17] Apropos this study, one could thus refer to inconsistent use of the DRPAD. From the highlighted areas, a further assumption is that pregnant radiographers may lack support with independently monitoring fetal dosages. Currently, the only technological support available for fetal dose monitoring is PC software from the service provider. This poses challenges to the radiographer in terms of access and privacy, whereby the software must be downloaded on a common computer in the department, which might be subject to power outages. Advances in mobile phone technology encompass all aspects of a computer, including wireless internet connectivity and vast accessibility to the population at large. The identified deficit in the literature is a lack of evidence of pregnant radiographers’ compliance with radiation safety viz dose monitoring of the fetus. The second identified deficit is that although many technological innovations have been created to monitor the health and wellness of a fetus and mother, such as mobile applications using smartphones, no mobile applications have been specifically designed for the pregnant radiographer to support monitoring of radiation dosages to the fetus. Lastly, the study assumes the pregnant radiographer might lack information about appropriate radiation safety and dose monitoring for the fetus. This would explain the reason why pregnant radiographers do not use their dosimeters properly and record the doses. Therefore, the suggestion arose to develop a mobile application to address the problem, as confirmed through the scoping review and situational analysis.

1.4 Research Question

The main, over-arching question this study attempts to answer is:

How can a mobile application be developed to enhance the recording and monitoring of fetal radiation doses as well as provide education regarding the usage of dosimeters to pregnant radiographers?

The sub-questions of the study as relates to the DSR framework are:

a) What methods are being used by pregnant radiographers to record and monitor the radiation doses to their fetus?

b) What processes must be followed in the development of the mobile application after the situational analysis?

c) What are the views of the mobile app end users regarding its useability and usefulness for fetal dose recording, monitoring and education?

1.5 Research Aim

The study aimed to develop a mobile application to enhance fetal radiation dose monitoring among pregnant radiographers.

1.6 Research Objectives

The objectives of this study align with the DSR research paradigm:

1. To understand the problem as it exists in the literature through narrative review problem awareness strategy
2. To perform a situational analysis on fetal radiation dose monitoring methods and radiation safety education among female radiographers in the clinical environment

3. To develop a prototype of the mobile application based on the suggestion
4. To determine the useability and usefulness of the mobile app for fetal dose recording, monitoring and education.

1.7 Theoretical Framework

Fulton et al.[18] describe a framework as a map that guides a study, providing the rationale for the development of the research question or hypothesis. Theoretical frameworks are described as "abstract generalisations" that encompasses at least two related concepts and thus can be used interchangeably with the term conceptual framework.[19, 20] Gray et al.[21] specify three approaches to constructing a framework: a) identify an existing theory from a discipline, b) synthesise a framework from existing findings, and c) propose a framework from clinical practice. In this study, the researcher critically analysed various theoretical frameworks with roots in the development of mobile applications within the information sciences discipline, namely the Behaviour change, User-centred design and Social marketing (BUS) framework, the Mobile Application Development Lifecycle (MADL) and the Technology Acceptance Model (TAM). Table 1 displays a summary of this analysis, whereby the frameworks are compared to each other to determine which would best meet the needs of the mobile application for this study.

Table 4: Comparison of mobile application theoretical frameworks

Conceptual frameworks	Authors	Problem identification	Health-Centred	Prototype development to address the problem	Testing of application in lab setting	Testing of application in natural environment
BUS	Hevner et al.[22] Patel and Arya[23]	✓	✓	✓	✓	✓
MADL	Vithani and Kumar[37]	✓	✓	✓	✓	X
TAM	Birkhoff et al.[24]	X	X	X	X	✓

As seen in Table 4, the BUS framework encompasses all the critical aspects needed for the development of the mobile application for fetal dose monitoring. The MADL framework is similar to the BUS framework; however, it includes maintenance as the end point of the mobile application, as opposed to testing. Therefore, this study utilised the BUS and MADL frameworks, whereby the BUS framework guided Development Cycle 1 and MADL guided Development Cycle 2.

1.7.1 Bus Framework

The BUS framework is described as a comprehensive tool for creating health applications[23]. The authors draw from three well-established theories, i.e., behaviour change theories, user-centred design and social marketing to create the BUS framework, which encompasses six steps that guide the creation of an artefact. The six steps are: i. Situational Analysis / Problem Awareness, ii. Concept Generation / Prototype Design, iii. Prototype Development, iv. Pilot Testing, v. Campaign Launch, and vi. Evaluation. In this study, the artefact developed is a mobile application.[23]

The BUS framework was considered suitable for this study as it has previously been used successfully to develop health-centred mobile applications owing to its comprehensive nature and inclusion of rigorous steps for artefact development[23]. In this study, the developed artefact is for pregnant radiographers to use in recording and monitoring their fetal radiation dosages. Based on the sensitive nature of the study population, it was imperative to use a comprehensive framework such as BUS in the development of the mobile application. The mobile application incorporates all aspects of the identified problem as well as testing, specifically in the development phase. Hence, the BUS framework forms part of the design science research framework, which is explained in the next section.

1.7.2 MADL Framework

The MADL framework provides a rigorous step towards the actual development of the final mobile artefact. Manuscript 3 of Chapter 4 elaborates on the MADL framework and its application in this study.

1.8 Research Paradigm and Philosophical Assumptions

Lincoln et al.[25] describe a paradigm as a set of beliefs that guide the actions and world view of the researcher. Design science research is a widely accepted research paradigm for developing mobile applications in information systems as it is used to create and evaluate artefacts that do not exist.[26] These artefacts are unique in that they are specifically aimed to solve organisational problems that emanate from the environment rigorously.[22] The next section explains the rationale for adopting the DSR paradigm.

1.8.1 Rationale for DSR as a Research Paradigm

Section 1 contains the description of the problem as it exists in reality—which can be referred to as an environment—supplemented with literature in Section 2.[22] This engendered the main problem identified in this study, namely inconsistent fetal dose monitoring among pregnant radiographers, which was confirmed through the situational analysis in Phase 1 of the study. Accordingly, the main aim of the study, and therefore suggestion (phase 2) is to develop a mobile application or artefact to address the identified problem. March and Smith[27] describe four historical outputs of design science research (DSR), namely constructs, models, methods, and instantiations. Instantiations refer to the realisation of an artefact in its environment.[27] The artefact in this study is the mobile application developed for use by pregnant radiographers to record fetal radiation doses. The study envisions that the mobile application will provide pregnant radiographers with a more consistent and reliable method of fetal dose monitoring regarding dose recording and storing and education on the proper usage of dosimeters. Hence, DSR design was the appropriate paradigm for two main reasons: a) It would provide a systematic, rigorous process for the development of a new mobile application designed for pregnant radiographers, and b) This mobile application would then provide a solution to the problem identified in the environment and will enhance methods of fetal dose monitoring, which could potentially save a fetus from over-exposure to radiation. One of the first applications of the DSR framework in radiography was successfully used for the development of an artefact for computer-aided detection (CAD) for chest pattern recognition training.[28] This further supports the use of the DSR framework in the radiography profession, as it has been proven to guide the development of successful artefacts. The next section describes the steps within the DSR processes.

1.8.2 The DSR Methodology Cycle

Vaishnavi[29] developed a widely used process to execute DSR research and explains the five steps in the process, namely a) Awareness of the Problem, b) Suggestion, c) Development, d) Evaluation, and e) Conclusion (Figure 1). These steps are briefly explained as follows:

a) Awareness: Can be derived from observation in the field of the discipline. It also emanates from the problem statement formulated in the research proposal, considering the observed problem and deficit in the literature.[28] Introduction and literature review map the awareness of the problem.[30] In this study, awareness of the problem is made through literature as well as through a situational analysis into fetal dosimetry practices among pregnant and previously pregnant woman in South Africa.

b) Suggestion: A preliminary design for the artefact in relation to the need it must address.[29] In this study the suggestion phase is guided by results from the problem awareness. It provides a tentative design constructed by the researcher that requires further refinement through the development cycles.

c) Development: The design was implemented to develop the mobile application (artefact). The BUS framework was incorporated within this step. This step also had two cycles, whereby the awareness, suggestion, development and evaluation re-occurred after developing every prototype of the artefact. These cycles occurred until the final one was satisfactory.[29] Two cycles occurred in this study.

d) Evaluation: A mandatory step evaluated against the suggestion phase. Therefore, it may lead to the refinement of Phases A, B and C, particularly if the evaluation is not satisfactory.[29] In this study, evaluation was conducted in the second cycle within the real-life setting. No amendments were made.

e) Conclusion: The final phase in which the artefact was presented, as well as the research process, construction and evaluation for research knowledge contribution.[29]

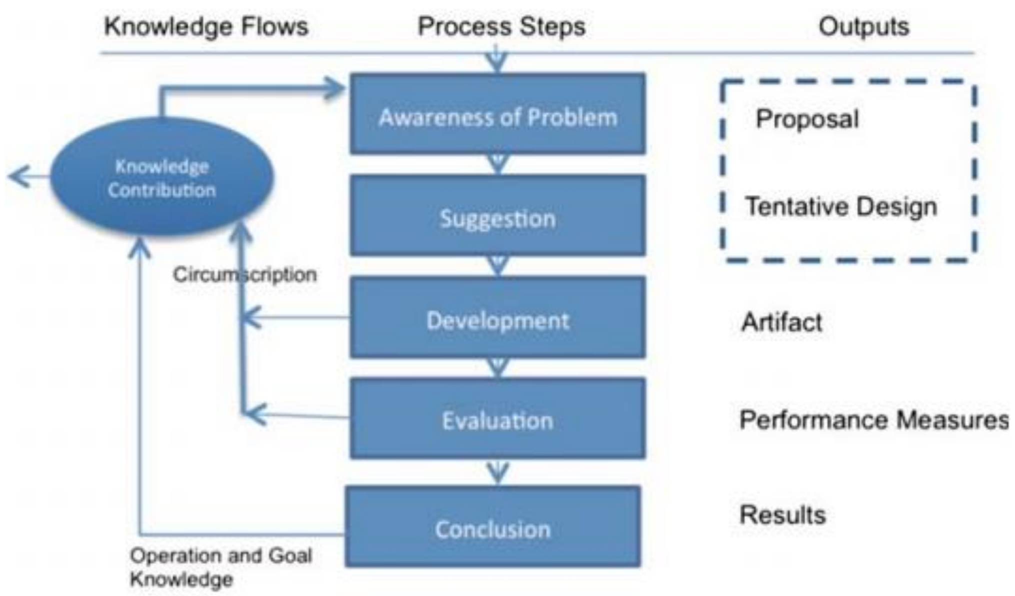

Figure 1:Design Science Research Process (DSR Cycle) by Vaishnavi[29]

In this study, the methodology was guided by the DSR process by Vaishnavi.[29] Figure 2 outlines the process used to create the mobile application for this study. As mentioned, Vaishnavi[29] stated that several cycles of the above processes can be executed in the development of an artefact. In this study, two cycles were included in the development stage, both of which incorporated steps from the BUS framework.

1.8.3 Cycle 1: In the first cycle, the BUS framework was followed through a design thinking approach to develop the prototype (mobile app version 1). Manuscript 2, Chapter 4 elaborates on this approach. All aspects of the cycle were guided by the end users' input and thus adopted a user-centred approach.

1.8.4 Cycle 2: In the second cycle, the prototype was analysed, and the final artefact was developed (mobile app version 2) using the rigorous processes of MADL, which is elaborated upon in Manuscript 4, Chapter 4.

Figure 2 below illustrates Cycles 1 and 2 within the development phase of the DSR process.

In the evaluation phase, participants who had engaged with the mobile application were interviewed, and the results were analysed.

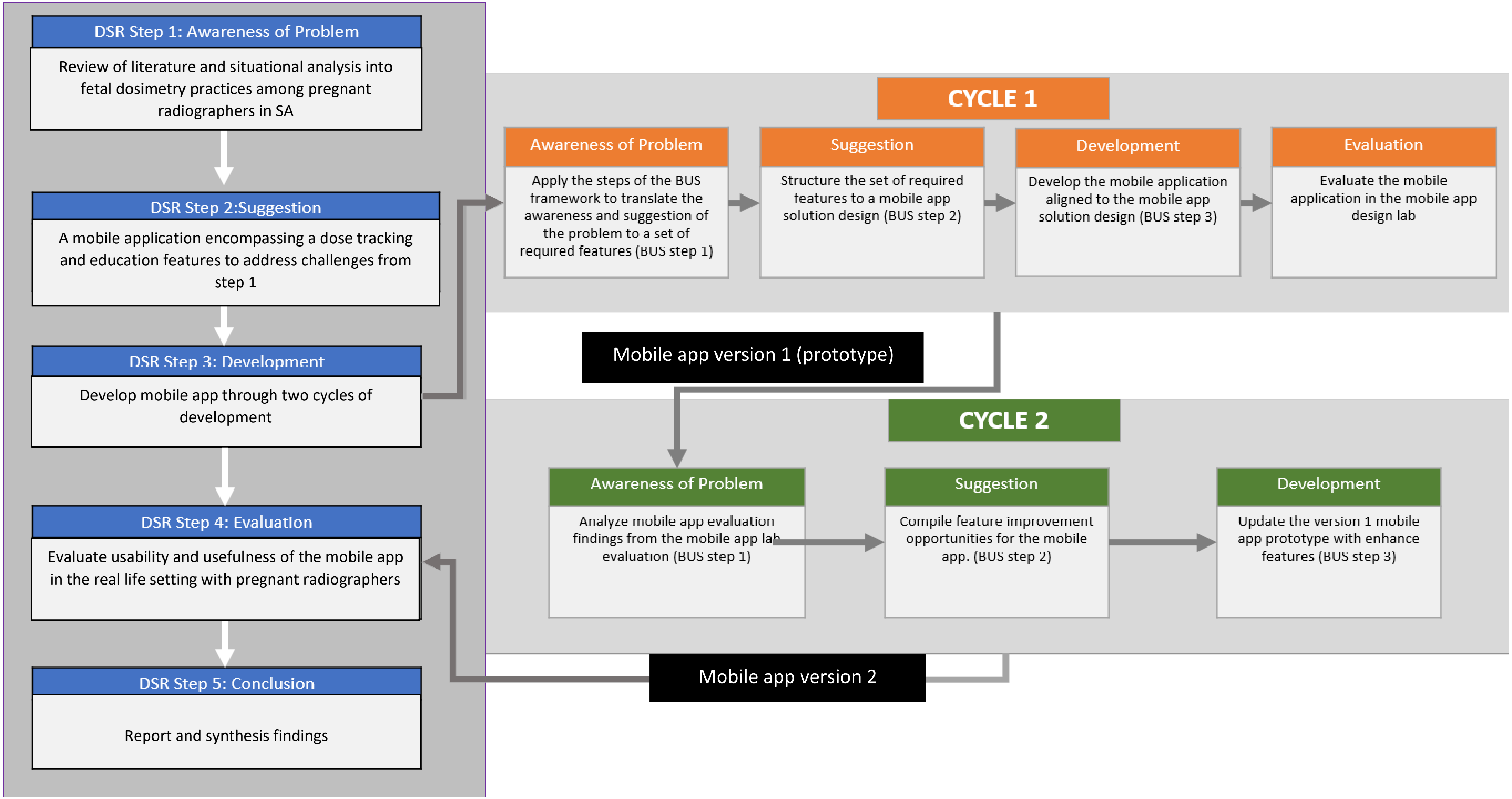

Figure 2:Summary of the DSR Process and Cycles that Guided the Study

1.9 Overview of the Research Methodology

The study followed a mixed-methods approach, which aligned to each step of the DSR design, as described above. Table 5 provides an overview of the research design, the instrument and the analysis methods used in each step. These steps are further elaborated on within each chapter of the dissertation, as outlined in Figure 3 at the end of Chapter 1.

Table 5: Overview of the research design, instrument and analysis method of the study.

DSR step	Objective	Design	Study population	Research instrument	Data analysis
DSR 1 **Awareness of Problem** **(Literature awareness)** **(Chapter 2)**	1. To understand the problem as it exists in the literature through narrative review problem awareness strategy				
Awareness of the problem **(Situational analysis)** **and** **DSR 2** **Suggestion (DSR 2)** **(Chapter 3)**	2. Perform a situational analysis on fetal radiation dose monitoring methods and radiation safety education among female radiographers in the clinical environment	Quantitative	All pregnant/ previously pregnant female radiographers registered with HPCSA in South Africa	Questionnaire	Descriptive analysis

DSR 3 Development (Chapter 4)	3. Develop a prototype of the mobile application based on the outcomes of the situational analysis	Development Cycle 1: Incorporation of BUS framework to develop first version prototype (Refer to Figure 2) Development Cycle 2: Development of second prototype (Refer to Figure 2)			
DSR 4 Evaluation (Chapter 5)	4. Determine the useability of the mobile app towards fetal dose monitoring, recording and education. 5. Explore the usefulness of the mobile app for fetal dose recording, monitoring and education	Qualitative	Female radiographers who have interacted with the mobile application	Telephonic, one-on-one interviews,	Content analysis
DSR 5 Conclusion (Chapter 6)	Reporting of results, limitations and recommendations				

1.10 Philosophical Assumptions

Philosophical assumptions guides the researchers' approach to the research question, determines the nature of concepts and influences the logic of the study[9]. Polit and Beck[10] describes assumptions as principles that are assumed to be true without scientific proof or verification. In the context of information technology (IT) four major philosophical assumptions exist namely ontology, epistemology, methodology and axiology[11].

1 10.1 Ontological assumption

Ontology is a patterned set of assumptions about reality[9]. In the context of this study the reality is that pregnant radiographers work in potentially hazardous ionizing radiation environments. The developing fetus's cells are sensitive to radiation, which places the unborn child at risk of a pregnant radiographer at risk if radiation doses are not carefully monitored throughout the pregnancy.

1.10.2 Epistemology assumptions

Epistemology is the theory of knowledge construction based on the researcher's view of the world around him or her[9]. In the context of IT, epistemology relates to how the researcher can relate to the object of construction[12]. For this study, the researcher herself is female radiographer who experienced challenges with fetal dosimetry during both her pregnancies. This evoked the need to explore potential objects of construction in order to solve the problem as it exists in reality.

1.10.3 Methodological assumptions

Methodological assumptions are ways of obtaining knowledge about the described reality. It is defined as a strategy, plan of action, process or design lying behind the choice and use of particular methods in a research project[9]. In this study, the DSR methodology was found to be appropriate to raise awareness regarding the problem, as well as to provide an intervention to solve the real-life problem.

1.10.4 Axiological assumptions

Axiology reflects the values of a researcher practising in science within the society that surrounds them to determine the extent of the development[11]. Science is object and therefore scientific truth is invaluable in research[11]. In this study, the researcher is a female who values the World Health Organisation's (WHO) Sustainable Development Goal (SDG) 3, namely good health and wellbeing, particularly that of maternal and fetal health. This serves as driver towards uncovering the real-life problem and finding a solution to it.

Scholars have accepted several worldviews, such as positivism, constructivism and pragmatism, to provide a philosophical underpinning for studies. Positivists believe there is a reality to all phenomena and that there must be an underlying cause and effect. In positivism, personal beliefs and biases are tightly controlled, together with a research approach, although fixed, can be constructed by research participants[31]. In pragmatism, the worldview orientates itself towards solving practical problems in the real world[32]. This study followed a pragmatic research approach; however, it also observed aspects of positivism and constructivism. Deng and Ji[33] explain that in DSR, researchers can observe more than one worldview while navigating different phases of the study. The upcoming section contains a discussion of these approaches.[33]

1.10.5 Pragmatism

Goldkuhl and[34] and Hevner et al.,[22] well-established as the founders of DS research, support pragmatism as the philosophical underpinning for DSR. Pragmatism refers to a worldview that incorporates a utility used to solve the problem and, in so doing, contributes to knowledge creation[34]. This study adopted pragmatism as the philosophical underpinning of the study since the utility being developed is the mobile application. The problem precipitating the study was pregnant radiographers' inconsistent fetal dose recording and monitoring methods. In addition, pragmatism is often associated with mixed-method designs, which was the design selected for this study.[32]

1.10.6 Positivism

In this study, the existing reality is the effect of X-radiation on cells in the body. In a positivist approach, a researcher seeks to identify a problem and solve it. Therefore, in the context of this study, the researcher identified the problem apropos to fetal radiation monitoring practices among pregnant radiographers. This was followed by the development of a mobile application to solve the identified problem. Paradigms are further characterised by how they respond to basic philosophical questions, namely ontological, epistemological and methodological.

1.10.7 Constructivism

This study assumes that pregnant radiographers do not have a consistent method of recording and monitoring their fetal radiation doses. This assumption is further supported by the lack of legislation in South Africa to guide pregnant radiographers on the method they should be using. Therefore, there is no fixed reality, but rather what was constructed by the research participants, who informed the researcher of the methods they were using, which, in turn, guided the mobile application design.

1.11 Ethical Considerations

Ethical consideration is an essential aspect of research as it provides guidelines for the researcher to consider in ensuring that the research undertaken is scientifically, ethically and legally sound.

The study gained ethical approval from the Faculty of Health Sciences Research Ethics Committee of the University of Pretoria, 632/2021 (Appendix F). Pregnant women have historically been excluded from research studies not directly related to pregnancy and fetal development because they are considered a vulnerable group. However, Van der Graaf et al.[36] (2018) indicates the necessity of including pregnant women in research studies, provided ethical principles have been duly addressed. These principles of ethics include autonomy, beneficence, non-maleficence and justice.

1.11.1 Autonomy and Confidentiality.

In medical research involving living participants, the researcher must honour the participants' right to make informed choices. In DSR Step 1 of the study, the researcher included an information leaflet and consent indicator (Appendix G) at the onset of the electronic survey (Appendix G). In Article 1 of Chapter 3, the study further elaborates on the ethical considerations for DSR Step 1. Privacy and confidentiality were maintained by anonymising the patients' details through coding, whereby each participant was assigned a number.

In DSR Step 4, the participants known to the researcher were invited to the participatory design workshop through email correspondence (Appendix H). The invitation included the programme (Appendix I). If the participants agreed to participate in the workshop, they were asked to access and complete a link to provide their details. In this step, the participants' names were revealed as they were considered contributors to the app and required acknowledgement in all dissemination of results (Manuscript 3).

In DSR Step 4, participants who had provided their details in DSR Step 1 for engaging with the app were contacted. In Manuscript 5 in Chapter 5, the study elaborates on the recruitment method for all other participants in this phase. By following a link, the interested participants accessed a summary information leaflet and consent form (Appendix J). This consent included both engagement with the app and a follow-up telephonic interview. Upon completing the link, the researcher further provided the participants with an elaborate guideline for using *PregiDose* (Appendix K) through email. Manuscript 5 in Chapter 5 provides a detailed description of the ethical considerations in this step.

1.11.2 Beneficence

Beneficence refers to upholding the participant's best interests during and after a study. The researcher ensured the participants' viewpoints and recommendations were considered when developing the mobile application. This was achieved by using the data generated from the participatory design workshop to inform the development of the final mobile app. Beneficence was also maintained by ensuring that the contributions of participants in DSR Step 3 were acknowledged. Lastly, in DSR Step 5, the app was made available to the participating pregnant radiographers to use in their natural settings, thus benefitting them.

1.11.3 Non-Maleficence

In research, non-maleficence entails a proposed study not causing harm to any of the participants or institutions who choose to participate. As mentioned in Section 15, pregnant women are considered vulnerable, and caution should be exercised to prevent either the mothers or fetuses from being subjected to any harm during or after the study. Manuscript 5 of Chapter 5 describes methods to ensure non-maleficence during DSR Step 4, engagement with the app in the real-life setting. In addition to the participants, the institutions also needed to be safeguarded from reputational harm. This was maintained in DSR Step 1, whereby participants were only required to indicate the type of institution in which they worked, namely private or public, and not the institution's name.

1.11.4 Justice

Justice refers to the participants' right to fair selection and equality, such that the selection of participants is based solely on the research requirements. In this study, justice was maintained by contacting the participants from DSR Step 1, who had provided their details for engagement with the app when it became available. Only a few were pregnant at the time DSR Step 4 commenced; however, it was still imperative to approach these participants first. Justice was also maintained in DSR Step 3 during the participatory design workshop, whereby a panel of various participants were invited to ensure equality and fair representation of all users who deal with aspects of pregnancy and radiation protection, as elaborated upon in Manuscript 3 of Chapter 4. Lastly, justice was maintained in DSR Step 4, whereby pregnant radiographers who did not have access to pregnancy dosimeters were still allowed to participate in the study and engage with other features of the mobile app.

1.12 Rationale

The occupational health and safety of pregnant radiographers and their fetuses encompass radiation protection by monitoring fetal doses effectively. Therefore, it was essential to ascertain how pregnant radiographers applied recording and radiation monitoring methods. Based on the identified deficit, a dose-monitoring mobile application was developed. The study arrived at the rationale for the mobile application in light of the rapidly increasing use of and access to smartphones, compared to computers and an internet connection, which are not readily available for personal use in some radiography departments. Notably, applications monitor many vitally important conditions requiring daily recording. In the context of this study, a mobile app can enable pregnant radiographers to transition from traditional paper-based recording methods to a digital platform, which can serve as a central, all-inclusive and more effective means of fetal dosimetry.

1.13 Significance and Contribution

The University of Pretoria's vision is to be a leading research-intensive university which focuses on local impact and international relevance. The development of the mobile application envisions using technology innovatively to provide a solution to inconsistent fetal dose monitoring among pregnant radiographers in South Africa. Such a technological solution would contribute towards enhancing radiation protection methods for the pregnant radiographer and thus improve occupational health and safety for both the mother and the unborn child, which aligns with the WHO SDG 3: Good Health and Well-Being.[35] The nature of the research is transdisciplinary, whereby the Faculty of Health Sciences, the Faculty of Engineering and Built Environment Sciences (EBIT), and industry (software developers) collaborated to achieve the goal of creating an artefact to solve a real-life problem. This realisation aligns with SDG 9, industry, innovation and infrastructure, as well as SDG 17, partnership for the goals. The research focused on the process, development and rigorous testing of the mobile application. All these objectives emanate from the research outputs in the form of articles and conference presentations and therefore contribute to the literature. Chapter 6 further elaborates upon the significance of the research and the research contributions.

1.14 Mapping of the Thesis Chapters

The research process and findings of this dissertation are presented commensurate with the thesis through the manuscript format of the Faculty of Health Science. Figure 5 provides a summary of the chapters and their corresponding manuscripts, whereby the DSR steps are embedded in each. The section further presents a brief overview of the different chapters.

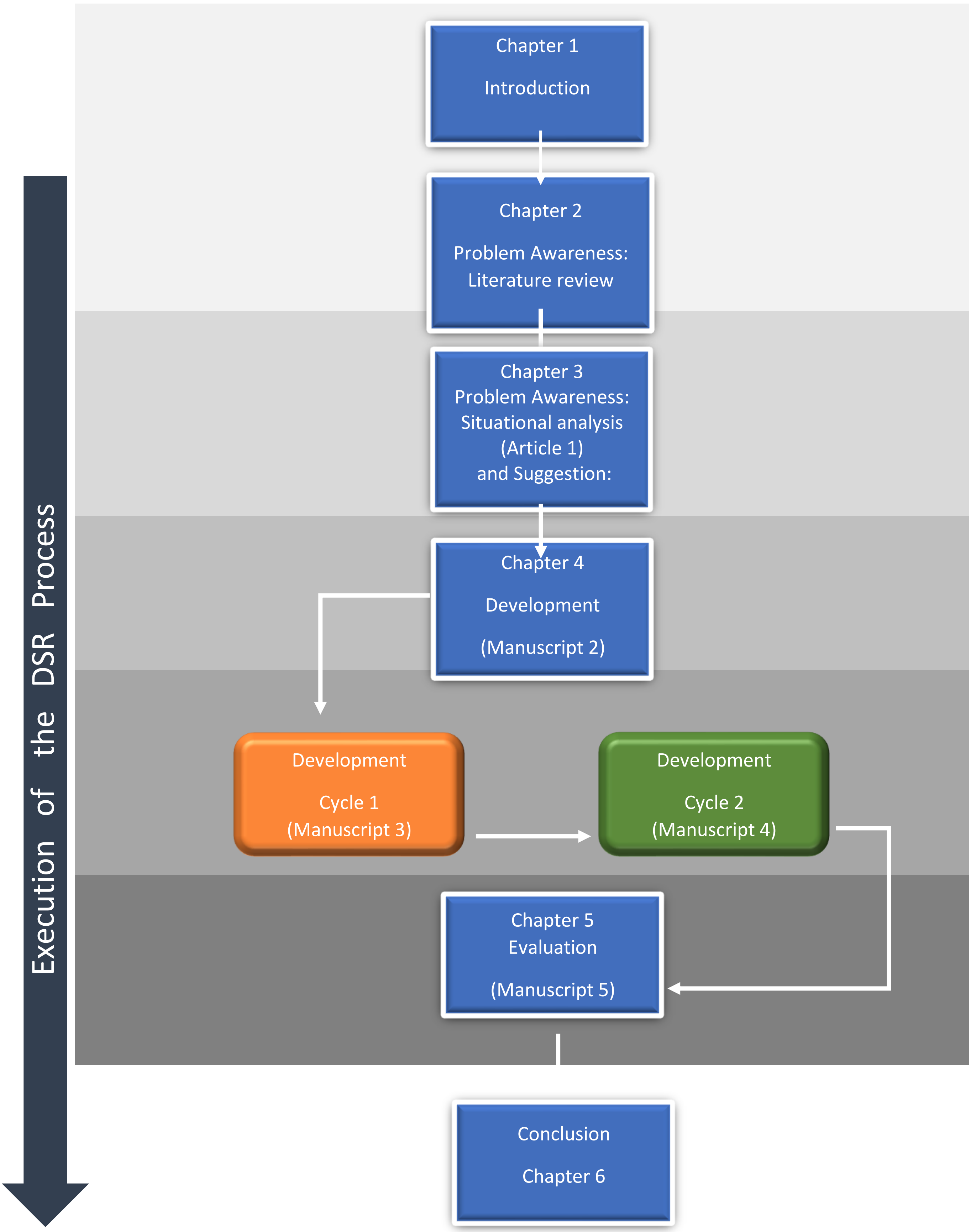

Figure 3: Mapping of Thesis Chapters Following the DSR Steps.

1.14.1 Chapter 1: Introduction and Background

This chapter provides an overview of the research focus area, the researcher's profile and the background of the study, which contributed to the development of the research problem. The chapter introduces DSR as a research paradigm and supporting framework and explains its application in this study in depth. The rationale, contribution and significance of the study are highlighted. A graphical representation of the thesis mapping is then presented, which serves as a guide for the upcoming chapters. The chapter then concludes with a summary of the contents of each chapter.

1.14.2 Chapter 2: Literature Review (DSR Step 1 – Problem awareness)

The chapter begins with an introduction to the concept of problem awareness and its application in DSR studies. Through the literature, the chapter then provides an overview of the key focus areas the problem awareness encompasses. Each of these focus areas is then expanded upon using literature cited both internationally and locally, sourced from different mediums such as journal articles, international and national policies and guidelines, and textbooks. The chapter concludes with the correlation between the problem awareness through literature and that observed in the real-life setting to reinforce the problem statement, whereby the identified research deficit is addressed using the second step in the DSR process, Suggestion.

1.14.3 Chapter 3: Article 1 (DSR Step 1 and 2 – problem awareness through situational analysis) and Suggestion

The chapter is presented in an article format, which encompasses a brief introduction and a methodology section regarding the situational analysis to bring awareness to the problem. The quantitative aspect of the mixed methods research design is elaborated on, and the research methodology and data analysis used for this particular step are explained in depth. The results are presented as descriptive statistics, followed by a discussion and conclusion.

The problem awareness through situational analysis is then followed by the suggestion step. The tentative design is described which features basic functions that need to be included in the app to address the problems identified in DSR step 1.

1.14.4 Chapter 4: (DSR Step 3 – Development)

This chapter comprises three manuscripts describing the development processes towards the prototype and final mobile application. As described in Sections 1.8.3 and 1.8.4, the development included Cycles 1 and 2.

Manuscript 2:

This paper presents a summary of the development phases, presented as a conference proceeding. The manuscript briefly describes the problem as it exists in real life, followed by the user-centred approach that was used to inform and develop the prototype of the mobile application.

Manuscript 3:

This paper describes the in-depth processes of Development Cycle 1 using the design thinking approach executed through a participatory design workshop to develop the mobile application prototype (mobile app version 1), which was used to guide the final development phase.

Manuscript 4:

This paper presents an extensive description of Development Cycle 2, using the mobile application development lifecycle (MADL) steps. Here, a technical report of the mobile application development is presented as the prototype (mobile app version 1), which was translated into a real-life functioning app (mobile app version 2).

1.14.5 Chapter 5: Manuscript 5 (DSR Step 4 – Evaluation)

This chapter is presented in manuscript format, providing a brief introduction and background. Chapter 5 further provides an in-depth description of the qualitative aspect of the mixed methods research design, including the research methodology and analysis specific to this step. In this phase, the participants engaged with the final prototype in its natural setting. They were then interviewed to assess the usefulness of the mobile application for fetal dose monitoring. The findings of this phase are presented as themes and categories.

1.14.6 Chapter 6: Synthesis of Findings

In this chapter, the researcher provides the main summary of the entire thesis. The research objectives and questions are referred to in relation to the research findings. The chapter then draws on the overall contribution of the research study to the radiography profession through information technology and then describes the limitations and future recommendations for the mobile application.

1.15 Chapter 1 Conclusion

This chapter provided a broad overview of the research to contextualise the research problem within the background, outlined the research aims and objectives, and provided a descriptive summary of the methodology. The chapter concludes by providing the reader with a visual map of the thesis. The thesis structure has a publication approach whereby the reader can expect article publications and manuscripts under review from peer-reviewed, accredited journals relating to each step of the DSR process.

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CHAPTER 2: LITERATURE REVIEW (AWARENESS OF PROBLEM) -DSR STEP ONE

2.1 Introduction

In this study, the first aspect of problem awareness takes place through the literature and secondly, through a situational analysis as part of DSR Step 1. The problem awareness will give rise to the suggestion (DSR step 2) which will serve as a tentative design for the development cycles.

a) Awareness through literature

The researcher first scrutinised the literature to understand dosimetry practices among pregnant radiographers and radiographers in general. The literature provides an overview of the cellular effects of radiation, with a specific focus on fetal radiation exposure, to provide a rationale for the exploration of this research. The chapter features a background to and timeline of investigating these effects on the offspring of pregnant radiographers as well as radiation protection regulations concerning the pregnant radiographer and her fetus. These are described by international and national regulatory bodies. Further, the chapter investigates compliance with these regulations, which leads to the rationale for the study. Table 6 presents the electronic search engines, databases and key terms used to search the literature.

Table 6: Electronic Search Engines, Databases and Key Terms Used to Search the Literature

Electronic search engines	*Pubmed*, *WorldCat*, *ScienceDirect*, Google *Scholar*, *ClinicalKey*
Databases	Scientific articles, journals, government policies, international and national radiation protection bodies
Key terms	Pregnant radiographer, radiation technologist, fetus, dose, stochastic effects, dosimeters, occupational health and safety, mobile application, healthcare, monitoring, in utero exposure

Radiation safety has been an area of concern dating back to the early 1900s, whereby the effects of radiation were noticed shortly after the discovery of X-rays.[1] The effects of in-utero exposure were first noted in the 1920s during pelvic radiation therapy, whereby a children were born with physical and mental impairments.[13] Later. experiments on pregnant lab rats revealed changes to embryonic developments on the fetus.[13] However, it was in 1945 during the Hiroshima and Nagaski bombings where threshold dose limits for detrimental in-utero exposure were established. Radiation effects from doses in the region of 500 mGy were found cause detrimental effects to the fetus, which will be described in section 2.1.2.

2.1.1 Cellular Effects of Radiation Exposure

Radiation effects on cells are classified into two categories, namely deterministic and stochastic effects.[2] Deterministic effects are caused by excessive radiation exposure to the tissue above the threshold limits; these effects are seen immediately and can cause visible skin erythema or cataracts. Stochastic effects are termed probable effects, as they have the potential to cause genetic harm; these effects result from exposures below the threshold level and can cause late effects, which result in genetic mutations or cancer.[2]

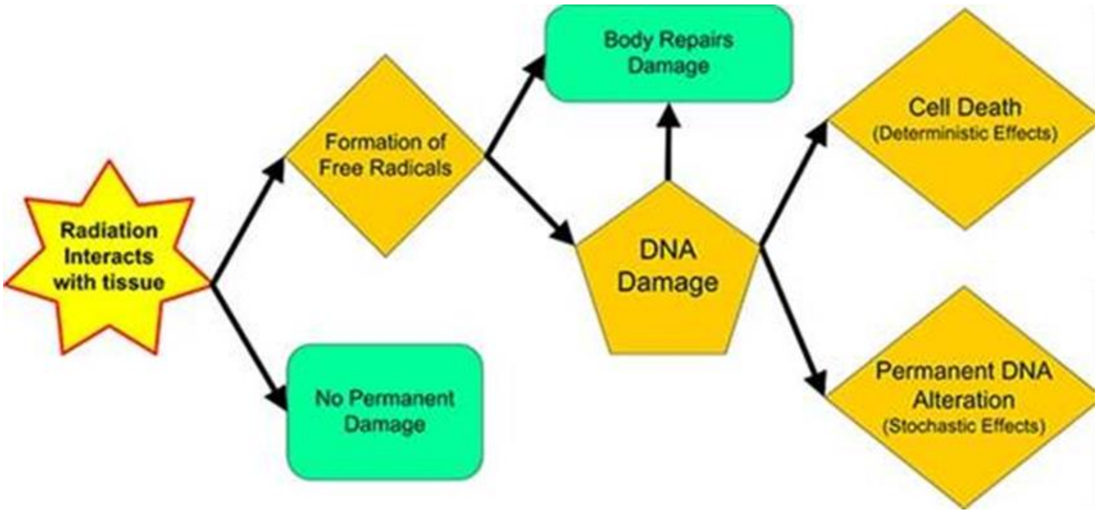

Figure 4: Radiation Effects on Cells[3]

Hence, the International Commission for Radiation Protection (ICRP) recommends that occupational exposure for radiographers does not exceed 20 mSv a year.[4] However, stricter radiation thresholds are applied for the fetus of a pregnant radiographer.

The radiation dose to a fetus is commonly described in literature as milli-gray (mGy). However in the context of radiation protection, doses are expressed as millisieverts (mSv). Milli-gray is the unit that expresses the amount of energy that ionizing radiation deposits into tissue and is therefore termed as absorbed dose. Millisieverts, however is the amount of effective dose calculated for the entire body. Effective dose has potential to cause biological effects and are therefore to referred to in the context of radiation protection[14]

2.1.2 In-Utero Radiation Exposure

A fetus is highly sensitive to radiation because of its rapidly developing cells, particularly during the organogenesis stage when cells are formed and during the embryonic stage when organs are developing.[5] Hence, radiation exposure above threshold limits can cause severe malformations. Dosimetry concepts for the purpose of radiation protection include collective dose equivalents, expressed as Sievert (Sv)[3].. Vu and Elder[6] describe these detrimental effects and their associated threshold limits, as presented in Table 7.

Table 7: Detrimental Effects on Fetus and Corresponding Threshold Doses [6]

Radiation effect	**Gestation (weeks)**	**Threshold dose (mGy)**
Embryonic death	3–4	100–200
Major malformations	4–8	250–500
Growth retardation	4–8	200–500
Irreversible whole body growth retardation	8–15	250–500
Severe mental disability	8–15 > 16	60–500 > 1,500
Microcephaly	8–15	> 20,000
Decrease in intelligence quotient	> 16	> 100

These doses are associated with direct radiation exposure. However, pregnant radiographers themselves are only allowed a threshold of 20 mSv of occupational radiation dose under the implementation policy,[4] which is well below the dosages described by Vu and Elder[6] to cause any detrimental deterministic effects to the fetus of a radiographer. The units presented in Table 7 are mGy. According to Adler[3], 0.01 Gy is equivalent to 0.01 Sv. It can therefore be accepted that units can be comparable. In Section 2.1.1, the probable risks associated with stochastic effects remain, whereby the offspring of radiation workers may suffer from genetic mutations or cancer. The study reviewed the existing literature on the radiation effects in the offspring of pregnant diagnostic radiation workers to identify any causal relationship between occupational radiation exposure, fetal abnormalities or cancer, as described in Table 8.

Table 8: Summary of Literature Review Investigating Radiation Effects in the Offspring of Radiation Workers.

Year	Authors	Title	Key findings
1996	Roman et al.[7]	Health of children born to medical radiographers.	No evidence of an excess or deficit in reported major malformations and cancer among the children and pregnancies of female radiographers. However within specific systems, two significantly high risks were found, both of which were largely due to a higher-than-expected number of adverse outcomes reported by female radiographers: 1. "other musculoskeletal" category 2. "chromosomal anomalies other than Down's Syndrome" group.
1997	Draper et al.[8]	Cancer in the offspring of radiation workers: a record linkage study	Mothers' radiation work was associated with a significant increase in childhood cancer compared to male radiographers, which indicated their exposure indeed contributed significant effects to their offspring. However, it was argued that the numbers are too small for reliable estimates of the risk, if any, to be made. It is presumed that the findings may be due to chance or some characteristic other than exposure to radiation.
2003	Sorahan et al[15]	Cancer in the offspring of radiation worker: An investigation of employment timing and a reanalysis using updated dose information	Timing of paternal employment revealed increased risk of Leukemia and non-Hodgkin's lymphoma is higher among children whose fathers were radiation workers either at the time of conception or diagnosis, and not among children whose fathers left radiation work before conception. Childhood leukemia rates are increased in areas of marked rural population mixing. (Location of nuclear sites)

2008	Johnson et al.[9]	Childhood cancer in offspring born in 1921–1984 to American radiologic technologists	Female and male RTs reported leukaemia (n=63) and solid tumours (n=115) in offspring; however, they were not associated with maternal in utero or preconception radiation exposure. No convincing evidence of an increased risk of childhood cancer in the offspring of RTs in association with parental occupational radiation exposure.
2009	Bunch et al.[10]	Cancer in the offspring of female radiation workers: a record linkage study (to Draper et al.[8])	The new data provide no evidence of an increased risk of childhood cancer associated with maternal preconception radiation work during pregnancy and thus do not support our earlier finding of a raised risk in the offspring of female radiation workers. However, the evidence is limited by the small number of linked cases and controls.
2020	Chartier H et al[16]	Occupational low-dose irradiation and cancer risk among medical radiation workers.	Higher risks of cancer were observed for pre-1950 exposure and for medical workers who performed fluoroscopically guided interventional procedures or radionuclides procedures compared to those who did not. Limitations: lack of dosimetry data, lifestyle factors and recent updates may obscure the link between medical occupational exposure and cancer occurrence. *Concerns of these studies is the lack of dosimetry reconstruction based on badge monitoring. Only the cohorts from the USA, South Korea, Denmark, Finland and Canada have access to complete or large individual exposure data. The other cohort studies either have no dosimetry information, or only self-reported information.

2023	Baudin et al [17]	Occupational exposure to ionizing radiation in medical staff: trends during the 2009–2019 period in a multicentric study	Radiation exposure of healthcare workers in most medical departments has steadily decreased between 2009 and 2019 in several French hospitals. The number of zero doses consistently increased during the study period. Workers in nuclear medicine departments are the most exposed, especially radiologic technologists and physicians.

Table 8 outlines six reviewed studies focusing on medical radiation workers and their offspring. The most current investigation into the effects of radiation-on-radiation workers' offspring the researcher found was published in 2023. This is where the interest in this research area emanates from, which not only focuses on investigating the effects of radiation on the fetus but also on the need for appropriate and improved monitoring. From these studies, it is evident that occupational radiation exposure to the radiation workers may be associated with increased risk of the offspring developing cancer, however these studies lack significant evidence to support this notion. However, it is important to note that although the cancer risk is minimal, there were indeed reports of some musculoskeletal and chromosomal abnormalities, which align with the stochastic effects of radiation. Also notable is that all of these studies had limitations, particularly regarding the small data pools employed. This finding draws on the views of Brent,[11] who stated that although the effect is minimal, it cannot be ruled out completely.

The ICRP supports this notion and states in Publication 103 [18];

"The weight of evidence on fundamental cellular processes coupled with dose-response data supports the view that, in the low dose range, below about 100 mSv, it is scientifically plausible to assume that the incidence of cancer or heritable effects will rise in direct proportion to an increase in the equivalent dose in the relevant organs and tissues"

Based on this statement, radiation protection bodies worldwide have not discounted the seriousness of radiation protection of pregnant radiographers, despite scientific evidence indicating that the risks are minimal; rather, the effects on tissue as a result of in-utero exposure to radiation is a developing research interest. Chartier et al[16] recommends that medical radiation workers should be more aware of the dosimeter reports in order to improve dosimetry practices. Manuscript 2 of Chapter 3 cites further descriptions of this. Radiation protection for the pregnant radiographer is guided by stringent compliance protocols established by international and national radiation regulatory bodies, on which the next section elaborates.

2.2 International and National Radiation Safety Guidelines for Pregnant Radiographers

According to the United States (US) Nuclear Regulatory Commission (NRC), fetal doses must be recorded at the beginning and end of each shift, and records from this device must be kept for three years by the licence holder.[12] The International Commission for Radiation Protection (ICRP) recommends that fetal doses should not exceed 100 mGy since that is associated with central nervous system malformations.[13] The ICRP document explains that although these levels are very uncommon, exposure can occur through direct fluoroscopy of the pelvis and radiotherapy.[13] Dewar[14] explains that radiation dosage to the fetus below 100 mGy bears a minimal to non-existent radiation risk of detrimental effects. However, due to stochastic effects, whereby radiation can damage a single cell—which can mutate over time—and increase the risk of cancer later in life, radiation authorities have adopted policies to regulate radiation monitoring and thus comply with occupational health and safety regulations.

In the United States of America (USA), when pregnant radiographers informally declare their pregnancy to their employer, they receive a “pregnant radiation worker declaration information packet” containing a formal declaration of pregnancy form and ordering of a fetal dosimeter, a device that measures radiation dose to the fetus.[1] In addition, the package contains the National Regulating Council Policy (NRCP) on information concerning prenatal radiation exposure and guidelines on the proper usage of the fetal dosimeter and film badge dosimeter for the mother.

In Nebraska, female radiation workers who declare their pregnancies are enrolled in a fetal monitoring program, whereby the employee is also given information from the NRCP, guidelines and training on the placement of the fetal dosimeter, as well as their personal dosimeters. Information is also provided on the mandatory recording and reporting procedures under ICRP and IAEA guidelines for pregnant radiographers. Sherer et al.[15] also concur with this procedure and further explain that the workplace should provide essential counselling on radiation safety measures, upon which the employee should sign a document stating they understand the practices with which they must comply.

In South Africa, radiation safety for pregnant radiographers is regulated by SAHPRA, who also align legislation with the above-mentioned international bodies.[16] The specifications of this regulation were outlined in the background of this document. These regulations make provision for monitoring the radiation doses to both the pregnant radiographer and her fetus.

2.3 Radiographer Compliance with Dosimeter Usage

As described in the introductory chapter, the thermoluminescent dosimeter (TLD) is used by all radiographers for monitoring radiation doses. A pregnant radiographer still utilises this monitor and has an additional real-time monitoring dosimeter for her fetus, which is a pocket alarm dosimeter (SAHPRA). Several studies have investigated radiographer compliance with wearing a dosimeter. In the United Arab Emirates (UAE), a study by Abuzaid et al.[17] investigated radiographers' adherence to radiation safety practices and identified that only 62.5% of radiographers used their dosimeters at work, with 15.7% never wearing them. A study in Iran revealed similar findings, with only 71.7% of radiographers using their dosimeters during practice despite them being accessible to all staff.[18] In South Africa, Modiba[19] investigated radiographers' compliance with radiation dose monitoring. Results from this study revealed that 35% of radiographers sometimes use their dosimeters, and only 59% always use them.[119] Modiba[19] explains that not only is noncompliance unacceptable and against regulations, but it also wastes valuable resources and increases health risks. Selemela[20] found similar results on non-compliance with dosimeter usage, with only 56% of radiographers wearing their dosimeters during a spot check in four academic hospitals in Gauteng.

These findings suggest that some radiographers seem negligent in using their dosimeters. However, it is unknown if pregnant radiographers comply with using their own dosimeters as well as the fetal dosimeters since they are responsible for protecting themselves as radiographers and also as child bearers. The use of a fetal dosimeter (DRPAD) requires self-monitoring. Should the radiographer not utilise the fetal dosimeter or capture the readings incorrectly, self-monitoring will prove to be ineffective, endangering the developing fetus. Many mobile applications have been developed to assist with recording data in aiding self-monitoring. The next section describes the benefits of self-monitoring mobile applications.

2.4 Self-Monitoring Through Mobile Applications

Smartphones, also referred to as mobiles, are the most widely used technology, with more than one billion smartphones globally.[21] Mobile applications in healthcare are intended to encourage users to monitor their health and wellness closely by enabling them to input and retain important information in a single, convenient place.[22] The use of mobile applications in healthcare is increasing rapidly, with more than 3673 apps exclusively dedicated to the eight most prevalent health conditions by the latest update (2004) of the Global Burden of Disease (GBD) of the World Health Organization (WHO), namely iron-deficiency anaemia, hearing loss, migraine, low vision, asthma, diabetes mellitus, osteoarthritis (OA), and unipolar depressive disorders.[21] In addition, mobile applications are also emerging in the fields of cardiology and radiation oncology for patients to self-monitor, thereby providing real-time information to the healthcare provider. Mobile applications for pregnant women also appear to be on the rise, with many pregnant women using applications as a central information hub as well as for monitoring the fetus in terms of its movement in the womb.[23] However, these applications are patient-focused and are termed mHealth, as they enable healthcare professionals to monitor their patients' health and well-being. Nevertheless, limited applications are available for the occupational health and safety of these health professionals, particularly for radiation workers. One particular study considered the healthcare needs of the citizens and employees who lived and worked near a nuclear plant in Japan. An advanced radiation monitoring application was then developed, which is described in the next section.

2.4.1 Advanced Radiation-Monitoring Mobile Applications

The study by Ishigaki et al.[24] indicates that mobile applications can be used to monitor and record radiation levels for the citizens residing around high-radiation nuclear power plants as well as staff working within them. In the South African context, high radiation doses are generated in departments such as Nuclear Medicine and Radiation therapy. Radiographers in nuclear medicine are issued with TLD badges (SAHPRA 2013); it is recommended that radiographers who are working directly with radionuclides are issued with finger TLD badges or electronic personal dosimeters.[25] Radiographers working in radiation therapy and diagnostic radiography departments must also be issued with TLD badges.[25] Therefore, it is evident that the use of a mobile application would apply to all pregnant radiographers working in nuclear medicine, radiation therapy and diagnostic radiography departments. Such a mobile application is currently not available in the market, which creates a need for the development of a self-monitoring mobile application for the South African context.

2.5 Chapter 2 Conclusion

This chapter exhibited that radiographers' occupational radiation exposure does not significantly affect the offspring of radiation workers; however, the risks associated with the non-probable stochastic effects of radiation remain. Hence, radiation authorities globally and nationally provide guidelines to support pregnant radiographers by ensuring they remain protected and within the safe threshold limits facilitated by fetal dosimeters. However, the reviewed literature uncovered non-compliance among the general population of radiographers regarding dosimeters, although limited research has been conducted on pregnant radiographers' compliance with fetal dosimeters, revealing a deficit in existing research. The chapter concluded with an exploration into the use of technology to support daily monitoring, which also revealed a lack of pregnancy fetal dose monitoring. These findings align with DSR Step 1, Problem Awareness through literature. The next section delves into the problem as it exists in reality, through a situational analysis.

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CHAPTER 3: PROBLEM AWARENESS (SITUATIONAL ANALYSIS) AND SUGGESTION

3.1 Introduction

Chapter 2 presented the deficiency in the existing literature, whereby it was evident that research on pregnant radiographers and dosimetry was lacking. This called for a situational analysis to uncover the complex adaptive systems that pregnant radiographers experience in the clinical setting of this context. The situational analysis therefore forms part of the problem awareness. The following article was published in the *Journal of Radiology Nursing* and presents the findings from the situational analysis, which addresses the DSR Step 2, Suggestion, as well as Objective 2 of the study.

3.1.1 Article 1

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Fetal Dosimeter Access, Usage, and Training Among Pregnant Radiographers in South Africa

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Keywords:
Pregnant radiographer
Occupational radiation safety
Fetal dosimeter
Radiation exposure
Compliance

A B S T R A C T

Background: Pregnant radiographers require more stringent occupational safety monitoring through fetal dosimetry because of the sensitivity of their fetuses' cells to radiation. This study aims to describe fetal dosimetry among pregnant radiographers as regards access, usage, and training.
Methods: Quantitative data were collected using an electronic national survey. The study collected 89 responses from pregnant and previously pregnant radiographers in South Africa between January 2021 and April 2021.
Findings: The responses revealed that 53.9% (n = 48) of participants had never been issued with a fetal dosimeter. This situation was mostly attributed to the employer and financial constraints (n = 29). Of those with access to fetal dosimeters, 46.1% (n = 41), only 56% (n = 28) indicated that they always wore it. An alarming 52% (n = 26) never consistently recorded fetal doses.
Discussion: Most pregnant South African radiographers do not have access to fetal dosimeters. Many of them remain noncompliant, which might be attributed to a lack of training and knowledge about the device.

Introduction

Radiation workers practice in potentially hazardous environments within radiology departments as a result of ionizing radiation used for diagnostic medical imaging (Sherer et al., 2017). Pregnant radiographers are considered high-risk individuals due to the increased sensitivity of the fetus's developing cells (International Atomic Energy Agency, 2022). Exposure to radiation has the potential to cause genetic effects and cancer within the fetus, depending on the amount of radiation dose received. A primary method of ensuring that occupational radiation doses remain within regulatory limits is through occupational radiation dose monitoring (American Association of Physicists in Medicine, 2019). This is achieved through personal dosimeters, also known as fetal dosimeters, which are worn by pregnant radiographers and provide real-time radiation dose measurements. A situational analysis done to investigate compliance of fetal dosimeters revealed that many pregnant radiographers, particularly in South Africa, lack support with regard to the training on the use of the dosimeter as well as consistent record-keeping of the fetal dose measurement. This barrier renders the device as ineffective and hazardous to both mother and the unborn child. Mobile applications offer a wide range of benefits and are often inculcated within an individual's life to ensure effective monitoring of any health needs.

Introduction

Radiation workers practice in radiology departments where they may be exposed to ionizing radiation used for diagnostic medical imaging (Sherer et al., 2017). Due to the increased sensitivity of a fetus's developing cells to radiation, pregnant radiographers are a category of radiation workers whom the International Committee on Radiation Protection (ICRP) (International Committee of Radiation Protection, 2000) and the International

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Atomic Energy Agency (IAEA) (International Atomic Energy Agency, 2022) designate to be prioritized for receiving radiation protection. This includes increased surveillance of the radiation exposure of both the pregnant radiographer and her fetus. The purpose of this paper is to report on fetal dosimetry in terms of access, usage, and training, particularly among pregnant radiographers in an upper-to middle-income country in sub-Saharan Africa.

In 2019, the American Association of Physicists in Medicine (AAPM) released a statement declaring that radiation doses used in diagnostic imaging are not associated with measurable harm to the gonads or fetus (American Association of Physicists in Medicine, 2019). Prashar, (2020) supported this statement and indicated that it is safe for pregnant radiographers to work in radiation environments, provided they practice safe radiation protection principles. The ICRP concurred, yet stated that this recommendation was based on the provision that fetal radiation doses are reasonably and accurately estimated and fall within the recommended limit of one millisieverts (1 mSv) (International Committee on Radiation Protection, 2000). This recommended threshold was established as relatively safe exposure that would not have considerable radiation-induced effects on a fetus.

Harmful Effects of Ionizing Radiation on a Fetus

The effects of radiation doses can be categorized as either deterministic or stochastic (Bushong and Facmp, 2020). Deterministic detrimental effects associated with excessively high radiation doses include pregnancy loss, malformation, developmental delay, and carcinogenesis (Yoon and Slesinger, 2019). Stochastic effects include probable effects resulting from low radiation exposure, since such effects can potentially cause genetic damage (Bushong and Facmp, 2020). According to the American Association of Physicists in Medicine, the radiation doses used in diagnostic radiography are sufficiently low not to pose any significant threat to the fetus of a patient (American Association of Physicists in Medicine, 2019). However, a distinguishing factor between pregnant patients and pregnant radiographers is the accumulated dose that a pregnant radiographer incurs during occupational work exposure. The risk of stochastic effects is heightened during the development of the fetus; therefore, it is important for a pregnant radiographer to monitor her fetal dose to ensure that threshold limits, as recommended by the ICRP (International Committee on Radiation Protection, 2000), are not exceeded. This monitoring is achieved by using fetal dosimeters.

Fetal Dosimetry

Thermoluminescent dosimeters (TLDs) are commonly used by radiography personnel and are considered passive dosimeters, whereby the exposure readout is only available after processing (Izewska and Rajan, 2005). However, pregnant radiographers must monitor radiation doses to their fetuses stringently and are thus required to use personal real-time dosimeters, also known as fetal dosimeters (Mohd Ridzwan et al., 2021; South African Health Products Regulatory Authority, 2022a). Radiation doses from these dosimeters can be viewed immediately through a visual display, rendering it more effective than TLDs at mitigating high exposure to irradiation (Butcher et al., 2015; Müller et al., 2014). A study by Khan et al. supports this view, finding a 36% decrease in radiation dose when using a real-time personal dosimeter (Khan and Yi, 2019). The use of personal real-time dosimeters in high radiation dose environments, such as catheterization laboratories as well as cardiac and orthopedic surgeries, is also growing, allowing personnel to visualize their radiation doses (Vano et al., 2011). These findings point to the added value that personal dosimeters offer to vulnerable groups, such as pregnant radiographers, compared to using routine TLDs independently (Koch et al., 2017).

Dosimeters can only be effective if health-care professionals wear them correctly (Jones and Ramirez, 2022) and receive the appropriate training on using the device (Durán et al., 2013). Karellas (2020) concurred with these findings, stating that if dosimeters are not used consistently, the accuracy of dosimetry and the analytical process might be compromised. Consequently, many studies have investigated noncompliance with dosimeter usage by general radiographers (McCulloch et al., 2018; Modiba, 2014; Mohd Ridzwan et al., 2021; Qureshi et al., 2022). Dosimeter usage and compliance by pregnant radiographers nevertheless remain an unexplored domain. Based on this limitation in the literature, the research investigated fetal dosimeter usage among pregnant radiographers.

Radiographer Compliance With Dosimeters

A study by Qureshi and Ramprasad revealed that an average of 94.4% (n = 221) of physicians admitted to not using a dosimeter (Qureshi et al., 2022). The physicians in that sample included radiation workers operating ionizing radiation equipment. McCulloch et al. (2018) further highlighted that 48% of radiographers attributed their noncompliance with dosimeter usage to “not remembering”. The abovementioned studies were conducted in the United States, where extensive dosimetry support is provided to pregnant radiographers. However, since compliance by radiographers generally appears to be low, it can be assumed that pregnant radiographers may also fall within this category. A limitation of studies exploring dosimetry includes the failure to indicate whether or not any pregnant radiographers had been part of such a research sample.

In contrast to high-income countries, middle-income countries, such as some Asian countries, have reported financial constraints as barriers to compliance with dosimeter usage. A study by Mohd Ridzwan et al. (2021) highlighted that fear of losing and having to replace an expensive dosimeter was a factor in noncompliance. Procurement challenges like delayed dosimeter supply due to late budget approval in the hospitals are also factors contributing to noncompliance. A study by Modiba (2014) further highlighted that only 59% of radiographers wore dosimeters. The scholar further reported that other health professionals, such as dentists, did not have access to dosimeters because employers were unable to provide them to employees (Modiba, 2014). Studies in low-income countries like Nigeria reported that only 50% of radiographers complied with wearing dosimeters (Eze et al., 2013). These statistics indicate that radiographers are complacent about the dangers associated with occupational radiation. Moreover, pregnant radiographers would be assumed to be more conscious of fetal radiation doses owing to the increased sensitivity of a fetus's cells. However, due to a lack of relevant studies, it is unknown how compliant pregnant radiographers are compared to their male and nonpregnant coworkers. The majority of the available literature on fetal dosimetry is related to the occupational guidelines and regulations for pregnant radiographers.

Occupational Radiation Safety Regulations for Pregnant Radiographers

Globally, radiation protection authorities, such as the National Council on Radiation Protection (NCRP) and the International Atomic Energy Agency (IAEA), continue to enforce radiation safety regulations for pregnant radiographers because stochastic effects still exist in the working environment. These regulations include using the necessary occupational health and safety devices, such as pregnancy dosimeters. Pregnancy dosimeters accurately measure the accumulative fetal radiation dose to ensure that the radiographers monitor their radiation doses and that such doses do not exceed the threshold limit. Pregnancy dosimeters include pocket reading alarm dosimeters, which provide real-time monitoring of fetal radiation dose (Prashar, 2020; South African Health Products Regulatory Authority, 2022b).

Occupational Radiation Support for Pregnant Radiographers

The United States of America, Australia, and Switzerland are considered high-income countries that spend a considerable amount of their gross domestic product on health care (Papanicolas et al., 2018). Such extensive financial resources allow countries like the United States of America to ensure sufficient support for pregnant radiographers working in potentially hazardous ionizing radiation environments. This is evidenced by pregnant radiographers receiving a Pregnant Radiation Worker Declaration Information Packet containing a formal declaration of pregnancy form and stating that a fetal dosimeter has been ordered (Koth and Smith, 2016). The package also contains the NCRP guidelines for pregnant radiographers regarding prenatal radiation exposure, instructions for using a fetal dosimeter, and a film badge dosimeter for the mother (Koth and Smith, 2016). In Nebraska (USA), pregnant radiology workers are enrolled in a fetal monitoring program that provides them with the NCRP guidelines, training on how to place the fetal dosimeter, and a personal dosimeter. Pregnant radiographers are also guided on how to record and report radiation exposure following ICRP and National Council on Radiation Protection and Measurements (NCRP) guidelines (International Commission on Radiation Protection, 2000; University of Nebraska Medical Center, 2022). Pregnant women are considered an underrepresented group in research studies (Blehar et al., 2013). In radiography, early investigations on the effects of radiation included the offspring of radiation workers (Bunch et al., 2009; Draper et al., 1997; Roman et al., 1996); however, a very limited number of studies investigating dosimetry concerning pregnant women exist (Prashar, 2020). For this reason, the researchers in this study investigated compliance with dosimetry by general radiographers as their frame of reference.

Pregnant radiographers are considered the most radiation-sensitive group of individuals as well as the most underrepresented group in research. Thus, it is necessary to understand the context in which such radiographers practice and whether their right to occupational health and safety is supported. Literature across high-, middle-, and low-income countries has suggested low dosimeter usage and, in some cases, a lack of access to dosimeters. However, existing literature on pregnant radiographers is extremely limited; therefore, the reference point regarding dosimeter usage is, of necessity, based on findings acquired from radiographers. This study aimed to investigate fetal dosimeter access, usage, and training among pregnant radiographers in an upper-to middle-income country in sub-Saharan Africa, through which recommendations could be made for ensuring the safety of both the pregnant radiographer and her unborn child. Hence, the study aligns with a key priority area of the World Health Organization, namely the “well-being of both mother and child” (World Health Organization, 2005, 2017), which provides the conceptual framework for the current study. The study can further be related to the United Nations Sustainable Development Goal 3: “Ensure healthy lives and promote well-being for all people at all ages.”

Methods

Study Design and Setting

A quantitative research design was adopted using a survey method. The study population included 6,886 registered female radiographers in diagnostic, radiation therapy, and nuclear medicine in South Africa, which is considered an upper- to middle-income African country (Group WB, 2014). The inclusion criterion for the study’s sample population was pregnant radiographers, and thus, the researchers employed a purposive sampling method to include only currently pregnant and previously pregnant radiographers. These radiographers could share their experiences regarding fetal dosimetry in their places of employment. The participants’ pregnancy statuses were not limited to a particular timeframe since this risked significantly reducing the sample size. Data were collected from January 2022 to April 2022. Women who reported never having been pregnant were not asked questions about dosimetry in pregnancy and were not included in the sample presented in this paper.

Data Collection Method

A self-formulated electronic survey was developed in consultation with the study’s supervisors and a statistician. The survey questions were derived from ICRP guidelines for pregnant radiographers (International Committee on Radiation Protection, 2000). The distribution of the survey included a snowballing method, whereby the survey was sent to the researcher’s fellow professionals and shared to social media groups specific to radiography, such as the South African Association of Radiographers, South African radiographers, and locum radiographers, for further dissemination. The survey aimed to ascertain pregnant radiographers’ access to, usage of, and training with fetal dosimeters during their pregnancies. The survey also enabled further probing into the factors causing barriers to dosimeter access and usage, with logical links wherever further explanation was required. The questionnaire had three options, categorized by the participants’ pregnancy statuses: 1) currently pregnant, 2) previously pregnant, and 3) never been pregnant. The survey incorporated logic links, which redirected the participants to another section of the survey based on their responses. The redirection was particularly applicable to category 3, “never been pregnant”, from which responses informed the second phase of a broader study not within the scope of this paper.

Accordingly, the dataset from categories 1 and 2 were used for the data analysis. The survey posed a series of questions to these participants related to their demographic, access, usage, and training with their pregnancy dosimeters.

Data Analysis

The raw data from the *Google Sheets* responses were downloaded in an *Excel* format (*xlsx*). Data from currently pregnant and previously pregnant radiographers were extracted and provided to the statistician. The IBM *SPSS Statistics* version 28.0.1.0 application was used to produce frequency tables (counts and percentages), and bar charts were generated using Microsoft *Excel* 2019.

Ethical Consideration

The study received ethical clearance from the University’s Faculty of Health Sciences Research Ethics Committee (635/2021). Pregnant women have historically been excluded from research studies not directly related to pregnancy and fetal development because they are considered a vulnerable group. However, Van der Graaf et al. (2018) indicate that it is necessary to include pregnant women in research studies, provided ethical principles have been duly addressed. Aspects of nonmaleficence and autonomy were adhered to during the recruitment and data collection processes of this study. The study was not a clinical trial but rather an analysis of fetal dosimeter access and usage by radiographers. Therefore, the potential for harm to any fetus was eliminated. The survey provided an information section and a consent selection option. Participants could only start answering the survey questions after they had consented to participate in the study; thus, the ethical principle of autonomy was adhered to.

Results

One hundred and forty-three participants responded to the survey. However, only pregnant and previously pregnant radiographers' responses were considered in the dataset, resulting in 89 responses from participants practicing in private or public institutions at the time of their pregnancies. Of the 89 responses received, 9 participants were currently pregnant, and 80 participants had previously been pregnant. Most responses (96.7%) were from diagnostic radiographers. The remaining responses (3.3%) were from radiation therapy and nuclear medicine radiographers. Most participants were radiographers working in public hospitals; 61.8% (n = 55) and 37.2% (n = 34) were from private hospitals.

Access, usage, and institutional support regarding pregnancy dosimeters.

Figure 1 illustrates the disparity in dosimeter access between private (n = 12) and public institutions (n = 29). In this study, 46.1% (n = 41) of radiographers had access to a pregnancy dosimeter during their pregnancies.

Fifty-three (53.9%) (n = 48) of the participants had not been provided with pregnancy dosimeters during their pregnancy. Participants were asked to provide an open-ended response with regard to the reason for not using a dosimeter. The reasons were largely attributed to employers not procuring the meters, as indicated by participants (n = 29) both in private and public hospitals. The extracted narratives described in Table 1 relate to the employers.

Usage

Among the 41 participants who indicated that they had received fetal dosimeters during their pregnancy, 56% (n = 28) reported always using the dosimeter, while 24% (n = 12) reported using it sometimes, and 20% (n = 10) reported never using the dosimeter (Figure 2).

Fetal dosimeters include pocket-reading alarm dosimeters providing real-time measurements that must be recorded by the radiographers according to the time limitation set by the radiographer. In this study, only 24% (n = 12) of participants who had received a fetal dosimeter (56%) indicated that they had recorded their doses daily. However, a concerning 52% (n = 26) of participants indicated that they never consistently recorded their fetuses' radiation doses, even though they had access to a pregnancy dosimeter (Figure 3).

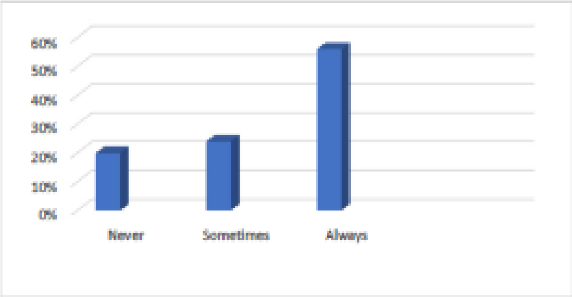

Figure 2. Fetal dosimeter usage by pregnant radiographers with access to fetal dosimeters.

Pregnancy Dosimeter Training

Table 2 presents the responses to whether the radiographers had training on the use of the fetal dosimeter. Seventy-four percent (n = 37) of participants who had access to a fetal dosimeter indicated that they did not receive training on its use.

Record-Keeping

Records of fetal doses must be stored and be accessible in the event of a fetus developing a congenital abnormality, in which case radiation records would be evaluated to identify instances of overexposure. In this study, radiographers had various inconsistent record-keeping methods, as presented in Figure 4. However, a concerning 36% (n = 18) of participants admitted to not keeping their fetal dose records at all, and 34% (n = 17) were unsure of where their fetal dose records were.

Discussion

The results indicate low usage of fetal dosimeters by pregnant radiographers. Factors attributed to this include limited access to fetal dosimeters, negative attitudes, and poor training on the use of dosimeters. The next section elaborates on each of these categories.

Access to Fetal Dosimeters

In this study, more than half of the participants indicated that they did not use fetal dosimeters. Most participants attributed this

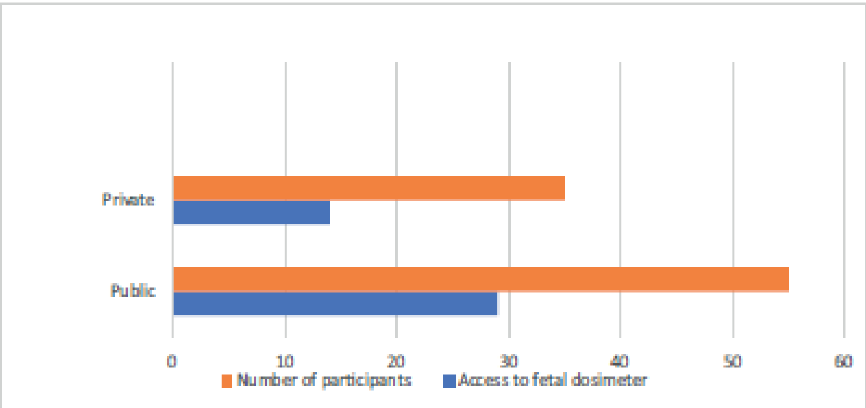

Figure 1. Fetal dosimeter access in private and public institutions.

Table 1
Employer-related factors for noncompliance toward pregnancy dosimeters

Direct quote	Source
Employer never provided	Diagnostic radiographer 9 previously pregnant/private practice
My company never used one before and said the TLD (thermolucent dosimeter) was fine	Diagnostic radiographer 10 previously pregnant/private practice
The department never had one/never procured	Diagnostic radiographer 11 previously pregnant/public institution
They were out of stock and some [were] faulty	Radiation therapy radiographer 30 previously pregnant/public institution
Company didn't want to buy—no money	Diagnostic radiographer 31 previously pregnant/private: medical sales representative
The practice did not have one, the previous radiographers did not wear one	Diagnostic radiographer 38 previously pregnant/private practice
None were available because we were a lot. They could not manage to give [to] all of us	Diagnostic radiographer 43 previously pregnant/public institution
It was not an option in the practice where I worked	Diagnostic radiographer 48 previously pregnant/private practice
The practice felt it wasn't necessary to have a separate dosimeter. We still had to go do mobiles as well while pregnant	Diagnostic radiographer 53 previously pregnant/private practice
I was told everyone uses the same dosimeter in the institution. Ten years later and many other pregnant radiographers, it has not been given to anyone ever in my institution	Diagnostic radiographer 93 previously pregnant/public institution
The hospital does not provide it anymore	Diagnostic radiographer 104 currently pregnant/public institution
There was nothing in place for pregnant radiographers in my department then	Diagnostic radiographer 121 previously pregnant/public institution
I was pregnant in 2004 and 2006 and we didn't have personal dosimeter in our department	Diagnostic radiographer 122 previously pregnant/public institution
Never given by manager. Not available at the time of my pregnancy	Diagnostic radiographer 125 previously pregnant/public institution

to their employers not having the funds to procure fetal dosimeters. Fetal dosimeters are often real-time pocket-reading dosimeters; the most expensive dosimeters cost around $870 for a single device. Radiography departments have evolved into female-dominant departments (Republic of South Africa, Goverment Gazette, 1993), with many women of childbearing age entering the radiography workforce. The use of real-time personal dosimeters has been proven to make its user more aware of radiation doses within their working environment (Butcher et al., 2015). This compels them to take further radiation protection measures toward reducing their exposure to radiation (Butcher et al., 2015). Hence, the aforementioned evidence supports the importance of female pregnant radiographers having access to fetal dosimeters. Dewar states that employers should provide pregnant radiographers with the appropriate protection to enable them to work in radiology settings without experiencing anxiety about harm to their fetuses (Dewar, 2013). The fetal dosimeter does not provide direct radiation protection to a fetus; however, it can alert the radiographer in advance of any radiation exposure that is accumulating beyond her threshold. This might prevent pregnant radiographers from becoming complacent about radiation because of its innate invisibility (Butcher et al., 2015). The ICRP states that pregnant radiographers are free to work in radiation environments, provided that their radiation doses can be reasonably and accurately estimated (Protection ICoR, 2000). The ICRP further mentions that the personal dosimeters worn by all radiographers do not provide accurate

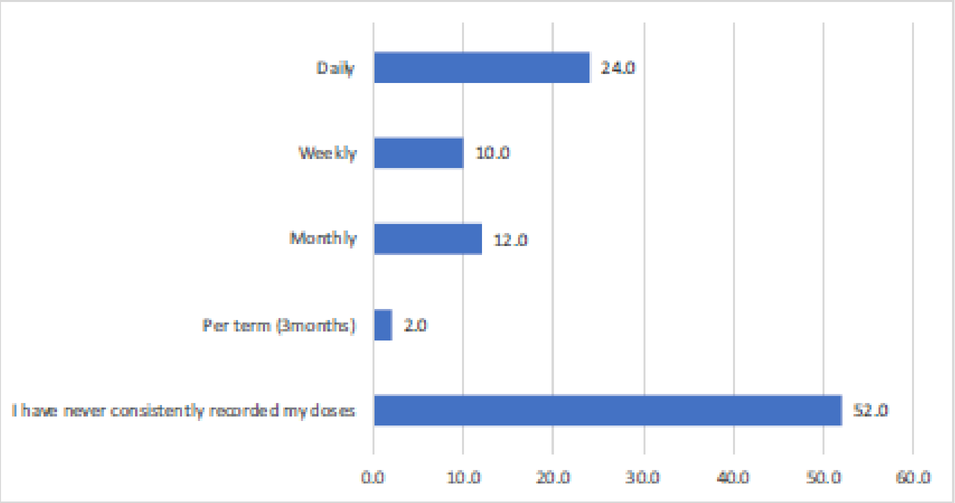

Figure 3. Frequency of fetal dose recording by pregnant radiographers who had access to fetal dosimeters.

fetal dose readings (Protection ICoR, 2000). This highlights that pregnant radiographers need dedicated fetal dosimeters specifically indicated for fetal readings. In South Africa, health regulatory authorities such as the South African Health Products Regulatory Authority further elaborate on the type of dosimeter required and state that "Pregnant radiographers must be issued with a direct-reading audible dosimeter, also known as a direct-reading pocket alarm dosimeter" (South African Health Products Regulatory Authority, 2022a). According to the Occupational Health and Safety Act 85 of 1993, employers are duty-bound toward "taking such steps as may be reasonably practicable to eliminate or mitigate any hazard or potential hazard" (Republic of South Africa, Goverment Gazette, 1993).

Therefore, it is evident that employers who do not provide employees with an effective means to measure fetal radiation doses are noncompliant with the occupational safety regulations pertaining to pregnant radiology workers. In contrast to the lack of access, some pregnant radiographers had indeed received fetal dosimeters from their employers yet were not fully compliant with their utilization.

Fetal Dosimeter Usage

The results revealed that only 46.1% of pregnant radiographers in this study had access to a fetal dosimeter during their pregnancies. Studies ranging from lower- to upper-income countries all report on poor compliance with dosimeter usage by general radiographers, both male and female. This indicates that dosimeter compliance is a global challenge, not only limited to developing countries and issues around access but also the employees' attitudes (McCulloch et al., 2018; Modiba, 2014; Mohd Ridzwan et al., 2021; Qureshi et al., 2022). Mohd Ridzwan et al. (2021) investigated the attitudes and beliefs of radiographers toward dosimeter usage. The scholars found that participants believed using a dosimeter was not as important as employing radiation protection measures; moreover, they believed that not wearing a dosimeter would not be harmful (Mohd Ridzwan et al., 2021).

In this research, the study population was pregnant radiographers; the developing cells and tissues of fetuses are highly sensitive to radiation (Sherer et al., 2017). Women are at peak fertility between their early teens and late 20s (World Health Organization,

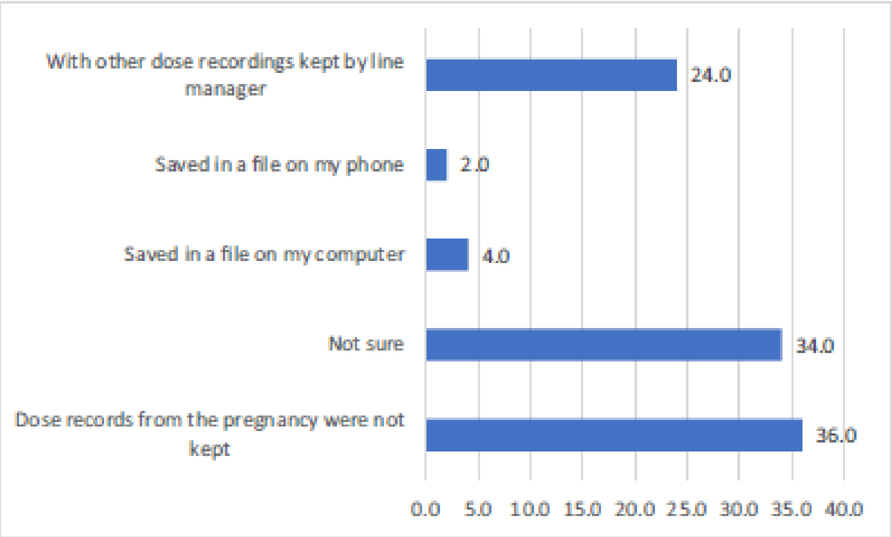

Figure 4. Pregnant radiographers' storage methods of fetal dose records.

Table 2
Frequency and percentage of participants who had received training on the use of the fetal dosimeter

Participant responses	Frequency	Percentage (%)
Valid		
No	37	74%
Yes	13	26%
Total	50	100%

2009). The radiography workforce comprises newly qualified young females of peak reproductive age. Considering this vulnerability, one would assume that the attitudes to dosimeter compliance of such young female members of this workforce would be heightened; however, based on the results of the current study, this appears to be the contrary.

Fetal Dosimeter Training and Dose Record-Keeping

In this study, most radiographers (74%) who were using fetal dosimeters had not been trained on the use of the device or how to keep records of such usage. In the United States, when a woman declares her pregnancy, she is provided with an information package and training by the employer (University of Nebraska Medical Center, 2022). In addition, pregnant women have access to radiation officers who can provide them with support on how to read doses (Vu and Elder, 2013). Nevertheless, in an upper- to middle-income country in sub-Saharan Africa, such as in this study, the findings revealed that many pregnant radiographers are not afforded this support.

Compliance with record-keeping was considerably low in terms of consistent record-keeping, with 52% (n = 26) of participants indicating that they never consistently recorded their fetal dosimeter readings. Subsequently, the overall fetal radiation dose could not be accurately estimated. The ICRP states that the overall fetal dose for the full duration of the pregnancy should be kept below 1 mSv. The results imply that inaccurate record-keeping places the fetus in danger inasmuch as potentially high radiation doses cannot be tracked.

Thus, the study demonstrated the assumption that limited training and, therefore, a lack of the requisite knowledge on how to use a fetal dosimeter might contribute to pregnant radiographers not consistently recording their doses. A study by Adhikari et al. (2009) supports this finding by associating poor personal dosimetry practices with a lack of knowledge regarding ionizing radiation. This study also found pregnant radiographers negligent with storing their recorded doses since 36% (n = 20) of the participants indicated not keeping their dose records (Figure 4). Radiation dose records play an essential role in monitoring and evaluating occupational radiation exposure and thus could contribute to enhancing radiation protection measures for radiation workers (Bhatt et al., 2012). The necessity of pregnant radiographers storing radiation records becomes significant should a child be born with a congenital abnormality.

Conclusion

Dosimetry among pregnant radiographers is an integral aspect of occupational radiation safety. This study found that some current and previously pregnant radiographers did not have access to fetal dosimeters. The most often cited reason was that employers were experiencing financial constraints despite operating in an upper- to middle-income African country. Some pregnant radiographers who indeed had access to fetal dosimeters still neglected to record their fetal doses consistently and accurately. This practice may be associated with a lack of training in the operation of fetal dosimeters. The study also found that many (% and n=) pregnant radiographers did not store their fetal dose measurements. These findings suggest that pregnant radiographers have limited knowledge of the potentially harmful effects of ionizing radiation on a developing fetus. This study recommends both a top-down and bottom-up approach toward improving access to fetal dosimeters, whereby radiation protection authorities enforce more stringent monitoring of employers regarding dosimeter access and training of pregnant employees. Radiographers must also be educated to a level of an understanding of their obligations to their unborn babies as well as their right as radiation workers to be provided with fetal dosimeters. These recommendations would promote the mitigation of the serious occupational risks to the female radiographer and unborn child associated with radiation exposure.

CRediT authorship contribution statement

Hafsa Essop: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Mable Kekana:** Conceptualization, Funding acquisition, Project administration, Supervision, Validation, Visualization, Writing – review & editing. **Hanlie Smuts:** Conceptualization, Funding acquisition, Project administration, Supervision, Validation, Visualization, Writing – review & editing. **Andries Masenge:** Formal analysis, Methodology, Project administration, Resources, Software, Supervision, Visualization.

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3.2 Suggestion– DSR STEP TWO

The findings presented in the awareness through literature and the situational analysis describe dosimetry practices, the dangers associated with ionizing radiation and the challenges experienced by pregnant radiographers. These include access to dosimeters, education and training on the dosimeter as well as support to improve their mental and emotional. The challenge related to access cannot be directly resolved through an app, however awareness of this problem through dissemination of results could potentially encourage employees to play a more proactive role at procuring the dosimeters.

The suggestion is therefore a mobile application as a technological invention towards enhancing fetal dosimetry methods for pregnant radiographers. The mobile app could be used to address challenges relating to fetal radiation dose monitoring and recording for pregnant radiographers who have PRADs'. The app will also provide education links and training resources related to ionizing radiation and occupational health and safety specific to the pregnant radiographer. This feature would therefore allow for pregnant radiographers who do not have access to a PRAD to still engage and benefit from the app. The tentative design of the mobile application therefore encompasses two core functional areas namely dose tracking and education links. However, the design of a successful app requires the input from the users themselves. Based on this reason, the first development cycle of the app will include a design thinking approach to inform the design of the app and assist the users in further identifying user needs that the app can address.

3.3 Chapter 3 Conclusion

The findings presented in this chapter describe inconsistent fetal dose tracking methods used by pregnant radiographers. They further highlight the lack of support given to pregnant radiographers regarding access and training on dosimeters. Thus, these findings support the need for developing a technological intervention that is both cost-effective and accessible. The suggestion provided is a mobile application that has core features that can address the real-life challenges. In the next phase, the suggestion will be advanced through two development cycles

CHAPTER 4: DEVELOPMENT OF THE MOBILE APPLICATION - DSR STEP THREE

4.1 Introduction

In Chapter 3, the findings from the situational analysis exhibited the challenges pregnant radiographers face while practising in potentially hazardous working environments. A mobile application was the suggested technological invention to address these challenges. Successful mobile applications follow rigorous design and development phases to ensure the final product is both useable and useful. Hence, this chapter comprises three manuscripts. The first one is labelled Manuscript 2. This manuscript provides a summary of both the design phase and development phase of the mobile application. Manuscript 3 further elaborates on the user-centred approach adopted during the designing of the mobile application prototype, and lastly, Manuscript 4 delves deeper into the technical aspects of the mobile application development and the final artefact, *PregiDose*.

4.1.1 Manuscript 2

This manuscript is a conference proceeding from the ICRP conference in Tokyo, Japan, in 2023. The researcher won the Cousins Award for Best Scientist and Professional with this presentation.

Session 5: The Next Generation of Scientists & Professionals

[Cousins Award Finalist] PregiDose: A Mobile Application Designed Through a User-Centered Approach to Enhance Fetal Dosimetry and Wellbeing Among Pregnant Radiographers

Hafsa ESSOP (University of Pretoria)*, Mable KEKANA (University of Pretoria), Hanlie SMUTS (University of Pretoria)

Abstract: Pregnant radiographers require more stringent radiation dose monitoring than general radiographers due to the sensitive nature of a developing fetus's cells to radiation. Occupational radiation safety measures are outlined for pregnant radiographers, such as limited practice in high radiation areas as well as the use of personal dosimeters to monitor and record fetal doses to ensure that the maximum threshold of 1 mSv of radiation is not exceeded. Compliance with pregnancy dosimetry is very low in South Africa, with many pregnant radiographers not receiving any dosimetry support, such as training on the dosimeter. This has led to the under-utilization of the personal dosimeter and the absence of fetal dose records among pregnant radiographers. This gap in fetal dosimetry called for the development of an intervention suited to the new technological generation, such as a mobile application.

Methodology: This study was executed in two phases. The first phase was a situational analysis of fetal dosimetry among pregnant radiographers in South Africa using a survey. The second phase was a Participatory Design Workshop (PDW) with a panel of twelve participants, who had an association with the research area, such as currently and previously pregnant radiographers, medical physicists, quality assurance managers, and the Radiation Regulatory Board of South Africa, among others. A design thinking approach and the FIGMA tool were used during the PDW, encompassing five steps, namely Empathy, Define, Ideate, Prototype, and Test, to develop a prototype mobile application tailor-made for the pregnant radiographer.

Results: Phase One: The situational analysis revealed that only 56% of pregnant radiographers "always wore" their personal dosimeters. An alarming 52% never consistently recorded their fetal dosimeters and 74% never received training on their personal dosimeters.

Phase Two: Using the design thinking process, it was revealed that pregnant radiographers do not understand how the dosimeters are used, which negatively impacts accurate dose-measuring. Further, pregnant radiographers lack an understanding of radiation effects on the developing fetus, making them complacent with effective fetal dose record-keeping. It was also revealed that pregnant radiographers felt isolated and "useless" in the workforce. In the ideate phase, the panel designed a prototype mobile application called *PregiDose*. This mobile application has features such as daily dose recordings, whereby dose measurements from the personal dosimeter can be inputted into the mobile application. Weekly and monthly dose reports can be generated, which can also be accessed by the employer.

1. Introduction literature review

Pregnant radiation workers are considered a vulnerable group due to the sensitivity of the developing fetus's cells to radiation (Blehar et al., 2013; Williams & Fletcher, 2010). Radiation workers practice in ionizing radiation environments that yield either high, moderate, or low radiation doses (Applegate et al., 2021; AAPM, 2019). These doses must never reach the stipulated radiation threshold dose limit for pregnant radiographers of 1 mSv (ICRP, 2000); however, the greatest fear remains the potential for this environment to yield radiation accidents (Applegate et al., 2021). Based on this reasoning, radiation protection for pregnant radiographers requires stringent monitoring. Both high-dose and low-dose fetal exposure have the potential to cause varying degrees of tissue reaction. The next section elaborates on these effects.

1.1 Effects of In-Utero Radiation Exposure

In-utero radiation effects can be classified as either deterministic or stochastic, determined by the amount of radiation the fetus has received. Experimental animal studies have revealed that high radiation doses can result in pregnancy loss, malformations, neurobehavioural abnormalities, fetal growth retardation, and cancer (Groen et al., 2012). In contrast, a study by Yasuda et al. reveals that in-utero low-dose exposure for pregnant women in the ranges of 1 to 2 mSv does not contribute towards congenital abnormalities, low birth weight, small for gestational age, or preterm birth. However, the stochastic effects of radiation remain a reality and have become a developing research area. The concern with stochastic effects is that they do not require a particular threshold limit and thus contribute to the '*fear of the unknown*' (Groen et al., 2012). A study by Fu et al. (2023) indicates that the fear of radiation effects acts as a maternal stressor during pregnancy, resulting in low birth weights and preterm deliveries. This aspect, together with physiological changes, alludes to the fact that women, and more so, female radiation workers, suffer from psychosocial challenges during their pregnancies.

1.2 Fetal Dosimetry Regulations

In light of the reality of the stochastic and deterministic effects described in the previous section, radiological protection bodies impose several regulations to guide practices and threshold limits for pregnant personnel in radiation environments. The ICRP Publication 84 is a highly revered publication, cited in the International Atomic Energy Agency (IAEA) and the South African Health Products Regulatory Authority (SAHPRA) guidelines for the management of pregnant radiographers and other staff members (SAHPRA, 2016). The document alleviates the fears of pregnant radiographers, providing reassurance that reasonable work can resume yet still providing the pregnant radiographer with the liberty to make decisions towards further protecting her fetus. This condition is predicated on the provision that the *'fetal dose can be reasonably, accurately estimated and falls within the recommended limit of 1 mGy fetal dose after the pregnancy is declared'.* A study by Essop et al. (2023) reveals that although these regulations are in place, many pregnant radiographers in South Africa are non-compliant, particularly regarding consistent fetal dose recording and reliable methods thereof. This concern called for an intervention that is both feasible for and accessible to pregnant radiographer

1.3 Mobile Applications in Healthcare

Mobile applications are rapidly growing in both developing and first-world countries because of their ease of access through smartphones (Martínez-Pérez et al., 2013). Mobile applications facilitate and support daily activities, often making users dependent on them. In healthcare, mobile applications are used to track and support many health activities for patients (Birkhoff et al., 2018); however, the use of mobile applications in occupational health and safety is evolving. Therefore, this paper presents an overview of the creative processes and scientific methods towards developing a technological advancement, namely a mobile application called *PregiDose*, to address these challenges identified in the situational analysis.

2. METHODOLOGY

The mobile application was executed over two development cycles: 1) A design thinking phase was executed through a Participatory Design Workshop (PDW) consisting of twelve participants. 2) A mobile application development lifecycle method with software engineers was used to produce the final artifact.

Each cycle's design and data collection methods are described in the upcoming section.

2.1 Prototype Development

This cycle followed a qualitative research approach with a design thinking methodology. This methodology encompasses five steps, i.e., empathize, define, ideate, prototype, and test (Altman et al., 2018). The data were collected during a participatory design workshop at the user experience (UX) laboratory at the Department of Informatics, University of Pretoria, to which twelve participants were invited. The participants were a heterogenous group consisting of the following individuals: pregnant radiographer (1), previously pregnant (3), never been pregnant (2), quality assurance officer (1), radiation board regulators (2), medical physicist (1), radiography department manager, (1) and *Figma* specialist (1). The participants engaged with activities in each step, guided by a facilitator to co-create a prototype mobile application using the *Figma* application. The *Figma* tool is a virtual real-time interface enabling users to create mobile application screens to visualize their concepts and ideas (Staiano, 2022).

2.2 Final Mobile Application Development

In this cycle, a custom mobile app for Android OS was developed with software engineers. The team consisted of a project/account manager, a UX designer, two software developers, and a test analyst. The cycle followed a mobile application development lifecycle (MADLC) methodology, which encompasses seven steps, namely identification, design, development, prototyping, testing, deployment, and maintenance (Vithani & Kumar, 2014). The identification phase included a face-to-face session with the team to present and elaborate the prototype recommendations in cycle one. In this step, the team generated ideas, shared knowledge, and narrowed down the features to the most important and feasible core functionalities. In the succeeding steps, the team worked on the design, whereby the software architecture and the app's appearance and behavior were designed, followed by rigorous testing and feedback sessions with the principal researchers. The final Andriod Package Kit (APK) file was then released, together with a promotional video providing an overview of the key functionalities of the app.

2.3 Ethical Consideration

The study received ethical clearance from the University of Pretoria, Faculty of Healthcare Sciences Research Ethics Committee. In Cycle One, all participants were invited and completed informed consent forms. Before the commencement of Cycle Two, the researchers engaged with the University of Pretoria Information Property Department to perform a patency check, ensuring that no other mobile application exists with the name *PregiDose*. Mobile applications with similar features were then compared to the prospective *PregiDose* app to ascertain areas of novelty and copyright.

3. RESULTS

The next section presents the results of prototype development and the final mobile application development cycle.

3.1 Prototype Development

In Cycle One, participants' field notes were collected and analyzed. In Step One, an empathy map was created through two users relaying real-life accounts of their experiences. Participants described pain points and fears, such as 'unsafe working environments', 'lack of knowledge' (User A), and 'loss of income' (User B). These factors allude to poor mental health and well-being among these pregnant radiographers. In Step Two, participants had to define pregnant radiographers' needs and provide insight into such needs. This action was followed by the ideate step, whereby the panel provided a solution to each problem that could be facilitated through the mobile application (Table 1).

Table 1: Participants' responses to the define and ideate steps of the design thinking methodology

DEFINE		**IDEATE**
Need	Insight	Dose tracker
Safe working environment (radiation protection measures)	Consistent and accurate dose-tracking methods	
Standard operating procedures on dosimeters	Which companies provide support for active dosimetry	
Knowledge of radiation safety measures	Helps the person understand how to protect herself	

Education and training on dosimeter usage	Many aspects of the dosimeter are unknown to the pregnant radiographer: ➢ Where to put it? ➢ How to interpret results? ➢ What to do when the dosimeter sounds an alarm	Education links
Empathy from the entire department	➢ The feeling of victimization or alienation, being gossiped about by colleagues. ➢ The feeling of uselessness, i.e., not being useful during pregnancy.	Psychosocial support links: ➢ Journaling ➢ Mindfulness ➢ Social media support groups

In the prototyping and testing step, the features of the ideate phase were applied to the *Figma* tool to produce screens. In this step, the participants created the name *PregiDose*.

3.2 Final Mobile Application Development

An elaborate specifications document was compiled from the data emanating from Cycle One. This stage involved software engineers and was executed through the six stages of development described in Section 2.2. Designing the appearance and behavior of the app was a continuous back-and-forth process to ensure that the logo was clear and meaningful. Three main functional areas were designed and coded: Dose tracking, Education, and Wellbeing. The dose tracking feature enables the pregnant radiographer to input a daily dose reading extracted from the dosimeter. The accumulative doses are then presented in a graph for the radiographer to visualize, thereby effectively monitoring dose readings throughout the pregnancy. The dose report can be generated and shared with quality assurance officers or managers in the event of an irregular reading. The education features provided several links to policies for pregnant radiographers in terms of radiation safety, as well as dosimeter guidelines and support. Lastly, wellness features provide psychosocial support, such as links to mindfulness practices, social media support groups, as well as journaling.

A promotional video regarding the app can be viewed on the following link:
https://www.youtube.com/watch?v=o_UeJdYqUOE

4. CONCLUSION

In this study, several phases of problem identification through situational analysis and empathy maps uncovered that beyond dosimetry, pregnant radiographers might be struggling with mental wellness because of the ethical dilemma of wanting to protect their offspring while remaining active team members within the radiography workforce. This ethical responsibility was heightened by the literature emphasizing a mother's responsibility toward protecting the fetus since the fetus had no part in the decision to become a radiation worker (ICRP, 2000). Nevertheless, this notion exists amid several studies indicating that a fetus' occupational radiation exposure is negligible, with no need for growing concerns. In light of this conundrum, the mobile application *PregiDose* was developed for the user by the user through a design thinking approach to address real-life challenges. The mobile application accommodates several pregnant radiographer needs. Its dose-tracking features enable the mother to be aware and cognizant of the fetus's daily dose exposures, thus enhancing fetal dosimetry practices. However, *PregiDose* goes beyond the dose and also accommodates pregnant radiographers' need for psychosocial support. Hence, the mobile application aligns with several of the World Health Organisation's Sustainable Development Goals (SDG) (Assembly, 2015), namely SDG 3, Good Health and Wellbeing—not only for patients but also for healthcare workers. SDG 9, Industry, Innovation, and Infrastructure, whereby the mobile application innovation opens up the possibility for other inventions that could facilitate occupational radiation protection. These innovations incorporating technical advancements can be adopted and incorporated by the industry. Lastly, the app meets SDG 17, Global Partnership. The vision and reality of *PregiDose* were accomplished through collaborative efforts between the information technology and radiation sciences, highlighting that both disciplines can be formidable partners in creating innovation.

Acknowledgments
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4.1.2 Manuscript 3

The findings from the situational analysis presented in Chapter 3 reveal the insufficiencies in the methods pregnant radiographers use to monitor and record their fetal doses. Thus, this manuscript addresses Objective 3 (Development Cycle 1), which is developing a prototype mobile application. This manuscript applies the BUS framework, as described in Chapter 1 of this thesis. Successful mobile application in healthcare requires a user-centred approach to inform the design of the prototype. Therefore, the manuscript elaborates on this process and its results through a design thinking approach. The manuscript is currently undergoing peer review in the *Health Informatics* journal and is titled:

Co-Designing of a prototype mobile application for fetal radiation dose monitoring among pregnant radiographers using a design thinking approach.

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Abstract

This study aimed to develop a prototype mobile application to enhance fetal dosimetry among pregnant radiographers in South Africa through a design thinking approach. Eleven participants were recruited to engage in a participatory design workshop, which encompassed five stages: Empathise, Ideate, Define, Prototype, and Test. The participants were divided into two teams. Qualitative datasets from the workshop included field notes and *Figma* screens. The data were analysed through thematic analysis, from which three major themes emerged: 1) Unsafe working environments for pregnant radiographers, 2) The need for enhanced fetal radiation dose monitoring by pregnant radiographers as an occupational health and safety requirement, and 3) Co-designing of the prototype mobile application, *PregiDose*. Consequently, the participants developed a prototype mobile application which addressed challenges experienced in the real-life setting. Hence, the prototype can be used as an effective framework by which to guide the development of the final artefact.

Keywords: Mobile application, pregnant radiographer, design thinking, fetal dosimetry, participatory design workshop

Introduction

Radiation workers practise in potentially hazardous environments within radiology departments since ionising radiation is used for diagnostic medical imaging (Sherer et al., 2017). Pregnant radiographers are considered high-risk individuals due to the increased sensitivity of fetuses' developing cells (IAEA, 2022). Radiation exposure has the potential to cause genetic defects and cancer within the fetus, depending on the amount of radiation dose received. The primary method of ensuring that occupational radiation doses remain within regulatory limits is occupational radiation-dose monitoring (McCulloch et al., 2018). The International Atomic Energy Agency (IAEA) stipulates that pregnant radiographers should monitor their fetal radiation doses to ensure that the threshold of 1 mSv of radiation is not exceeded (IAEA, 2022). Thus, pregnant radiographers are required to wear personal dosimeters, also known as fetal dosimeters, which provide real-time radiation dose measurements (Butcher et al., 2015). These daily doses must be recorded manually by the pregnant radiographer using a method of her choice, such as a logbook (Singh, 2003).

Mobile application technology

In an era of technological advancements, mobile applications have rapidly replaced paper-based recording. The key feature of mobile applications is their ability to input daily readings of any variables that can be stored, analysed and presented statistically for the user to monitor their health (Peake et al., 2018). This enables individuals to incorporate mobile applications into their daily activities (Lin et al., 2021). This advancement has precipitated the replacement of many desktop applications because of the ease with which the same task can be performed using a mobile device (Lin et al., 2021). In addition, mobile applications are easily accessible to the wider population, with the release of affordable smartphones in both first-world and developing countries (Lin et al., 2021). Medical applications on smartphones are widely used, and their functionalities are proven to transform healthcare (West, 2012; Zhang et al., 2022). Mobile applications also have the potential to improve occupational health and safety, provided the input and output data can be used to mitigate hazards (Reyes et al., 2016).

The benefits of technology can be extended to healthcare workers, particularly pregnant radiographers working in ionising radiation environments. The replacement of manual fetal dose recording with a mobile application on a smartphone is, therefore, an appropriate technological innovation that can be used to facilitate radiation protection for pregnant radiographers and their unborn children. The development of this novel mobile application required careful thought processing focused on the user and thus incorporated the design thinking approach.

Design thinking approach to mobile application development.

Design thinking is a user-centred approach involving the target population to inform and guide the design of an artefact (Morko-Holguin et al., 2019). In healthcare, innovations are often developed top-down without consultation of the end-user, resulting in the underutilisation of the particular artefact (Altman et al., 2018). However, the design thinking methodology provides a more inclusive approach to creating artefacts, i.e., for the user by the user (Altman et al., 2018; Kamran & Dal Cin, 2020). This approach further bridges the gap between two disciplines, namely healthcare and informatics, whereby empathy towards the user is considered and understood by the researcher (Altman et al., 2018), and the design of the artefact is thus tailor-made by the designer to meet the end-users' needs (Razzouk & Shute, 2012). Furthermore, other studies utilising this approach within the radiology context find it a successful approach (Deitte & Omary, 2019).

Design thinking prioritises empathy in understanding the users' context, which can be used to develop creative solutions. Design thinking encompasses user-centred iterative sessions with multidisciplinary teams to gain multiple perspectives on the topic of interest using the concept of ideation (Kamran &

Dal Cin, 2020). Such an approach often adopts qualitative data collection methods, such as focus groups, interviews, cultural probes and brainstorming sessions to enable the user to co-design a potential artefact, such as a mobile application. Data from these sessions are used to ideate solutions to the problems identified. These solutions are then tested with the target population in the form of "action-orientated rapid prototyping" through several rounds of ideation (Altman et al., 2018). Accordingly, the design thinking process encompasses five phases, namely 1) Empathise, 2) Define, 3) Ideate, 4) Prototype and 5) Test. A summary of the scope of each of these phases within this study is described in Figure 1. Each of these phases is explained in depth in the upcoming sections. Therefore, the purpose of this paper is to describe the creative thinking process involved in creating the prototype of the fetal radiation dose monitoring application.

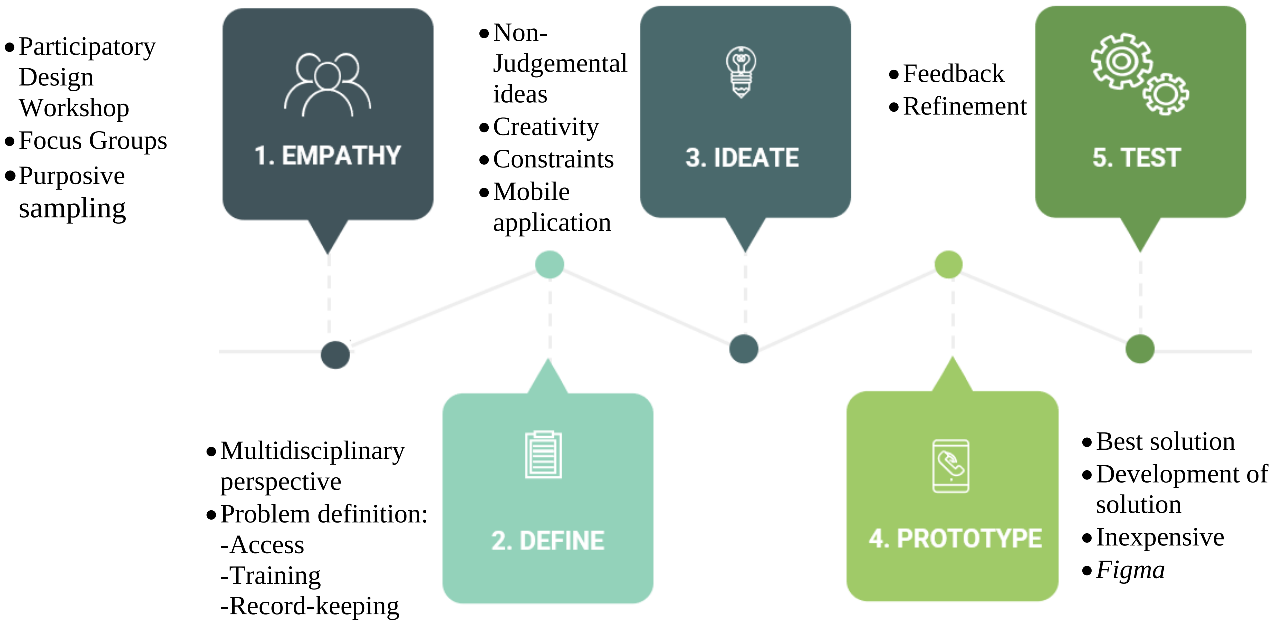

Figure 1: Summary of the design thinking process for the development of a fetal radiation dose monitoring mobile application.

ETHICAL CONSIDERATION

The study attained ethical clearance from the University of ###, Faculty of Health Care Science (635/2021).

METHODOLOGY

A qualitative research approach was adopted and executed through a participatory design workshop. Research workshops can be defined as a gathering of a group of people to generate data to solve a problem (Ørngreen and Levinsen, 2017). Participatory design workshops (PDW) are utilised when an artefact needs to be developed through a user-centred approach, such that the product is designed specifically to meet the user's needs (Razzouk & Shute, 2012). The uniqueness of workshops in qualitative research is their ability to foster engagement between the participants and facilitators, whereby experiences, ideas and solutions can be discussed non-prejudicially (Ahmed & Asraf, 2018). This enables the participants to co-design an artefact while the researcher still controls the core functionalities of the product. The facilitator plays an integral role by encouraging meaningful engagement during these prolonged and intensive sessions (Ahmed & Asraf, 2018). In this study, the chosen facilitator had vast experience in participatory design workshops using the design thinking approach, as well as extensive knowledge of information technology.

Participants and sampling

A purposive sampling method was used to select individuals with specific characteristics related to the research focus area (Creswell & Creswell, 2017). Eleven participants attended the workshop. The participants included: A pregnant radiographer (n:1), previously pregnant radiographers (n:3), never been pregnant radiographers (n:2), quality assurance managers (n:1), radiography department managers (n:1), a medical physicist (n:1) and Radiation Board Regulatory Officers (n:2). The workshop was conducted at the User Experience (UX) laboratory at the Department of Informatics, University of #### on the 13th of January 2023, commencing at 08h00 and finishing at 16h00.

DATA ORGANISATION AND ANALYSIS

The datasets generated from the workshop included drawings, field notes from Team A and Team B, as well as virtual *Figma* screens designed by the participants. The drawings were considered facilitation exercises to initiate the collaborative process and were not included in the data analysis. A total of 15 field notes were gathered. The field notes from Teams A and B were separated and identified by differently coloured text. The field notes from each team were then organised in the order of the execution of the design thinking steps.

The qualitative analytical methods used for this study included user personae and thematic analysis. User persona is a technique used to understand the user by creating a profile of them that can be used to describe their experiences, characteristics and attitudes (Ferreira et al., 2017). In this study, user personae were created using the interview field notes, upon which the researcher elaborates in the data collection section. Thematic analysis was employed in the proceeding steps to identify codes that can be used to categorise the participants' patterns of thoughts, feelings and experiences (Braun & Clarke, 2018).

The researcher conducted both analyses, which were further verified by the supervisors and facilitators. The researcher was purposively excluded from the workshop to guard the integrity of the data, such that the participants would not be influenced by the researcher's knowledge and preconceived ideas. This enabled the researcher to be part of the analytical process.

Data availability

The field notes from the participatory design workshop can be made available by the researcher upon request.

DATA COLLECTION METHOD

The PDW was facilitated by a professional in information technology, who planned the activities for each of the five steps of the design thinking process. The participants and facilitator introduced themselves, and the facilitator divided the group into two teams, Team A and Team B (Figure 2).

a) b)

Figure 2a) and b): Teams A and B during the participatory design workshop

Teams

The participants in each team were purposively selected by the facilitator to ensure an equal distribution of gender and professions and to create a multi-disciplinary team. This form of collaboration was necessary during the PDW as it generated innovative ideas between professionals within that space. The teams were then briefed on the design thinking methodology and the objectives of the day. The facilitator started the session with an activity to unlock the participants' creativity as innovators. In the activity, the participants had to draw interpretations of keywords related to the research focus area, namely 'Baby', 'X-Ray' and 'Innovation'. Figure 3 illustrates the participants' creative perceptions of these keywords.

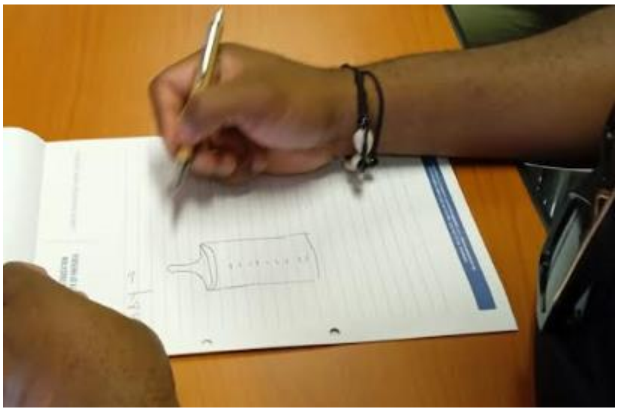

Figure 3: Unlocking participants' creative potential.

At that juncture, the participants were at a point of comfort, which facilitated the first crucial step of design thinking, namely Empathy.

Step 1: Empathy

Empathy requires understanding the user's challenges and needs in their everyday life (Altman et al., 2018). To engender empathy, participants from each team were asked to select a 'user' within their team representative of the research area of interest. The participants were tasked with interviewing the user non-judgmentally to explore her experiences as a pregnant radiographer.

Step 2: Define

In this step, the problem was defined to develop the appropriate solution (Deitte & Omary, 2019). The Define step was informed by two important factors, namely user needs and insight into why this presents as a need. These factors were combined to create a summarised 'Point of View Statement (PoV)', which defines the user's main problem.

Step 3: Ideate

In this step, participants were required to formulate broad ideas to generate a solution to the POV. This step was a high-energy activity involving brainstorming and sharing ideas among the multi-disciplinary team.

Steps 4 and 5: Prototyping and Testing

In Steps 4 and 5, the selected ideas were used to formulate the prototype mobile application. The advantage of prototyping is the opportunity to test a product early on and for it to fail early on, such that minimal time and cost are invested in the event of such a product failure. It further provides an opportunity for early testing and making improvements. In this PDW, prototyping was executed through the *Figma* tool (to be further explained).

Figma

Figma is a powerful collaborative tool that enables designers to create a user interface quickly and cost-effectively (Staiano, 2022). This study recruited a *Figma* specialist to facilitate the session, whereby the participants provided real-time feedback, after which the specialist made amendments to the prototype. Such amendments included its 'look' and 'feel', as well as feature links addressing specific user needs. The prototype was also tested during this phase, whereby participants had the opportunity to engage with the features and make recommendations thereof.

RESULTS

The results of the workshop are presented as Team A and Team B, in order of the design thinking process. The narrations presented were thus collectives as a group, not individuals. The data analysis process started by identifying codes and then categories. Relating the categories to the research objectives led to the emergence of three major themes, namely 1) an unsafe working environment for pregnant radiographers, 2) the need for enhanced fetal radiation dose monitoring among pregnant radiographers as an occupational health and safety requirement, and 3) co-designing the prototype mobile application: *PregiDose*. The themes are presented next.

Theme 1: Unsafe working environment for pregnant radiographers

This theme emerged from the selected ‘user’ from Teams A and B, which was used to create two user personae, presented in Figures 4 and 5, respectively. These personae are real-life encounters of each group’s representative, who provided detailed descriptions of the background and pain points the user had experienced.

User A

User A was a theatre radiographer. She found out she was pregnant at four to five weeks; however, she only disclosed her pregnancy at 18 weeks. Personal protective equipment was available; however, personal radiation monitors (dosimeters) were not provided.

<u>PROFILE</u>

Children: 3
Job title: Theatre radiographer
Employer: Private
Pregnancy status: Previously pregnant

Pain points: Fears

- Prejudice
- Fetal deformity
- Loss of income
- Victimised
- Uselessness
- Lack of knowledge

Environment

- Unsafe
- Unsupportive
- Personal protection – purchased own dosimeter.

Figure 4: Team A user persona

User B

User B is currently pregnant and practising as a theatre radiographer. She found out she was pregnant at three weeks. Due to the lack of support for pregnant radiographers, she resigned immediately.

<u>PROFILE</u>

Children: 1
Job title: Theatre radiographer
Employer: Private
Pregnancy status: Currently

Pain Point - Fears

Prejudice
Fetal Deformity
Loss of income

Environment

Unsafe
Unsupportive
Protection of employer

Figure 5: Team B user persona

The above two personae are from two users who, in real life, were pregnant at different times and worked for different employers. The findings from this empathy map indicate that they shared the same fears, mostly emanating from the same source.

Theme 2: The need for enhanced fetal radiation dose monitoring by pregnant radiographers as an occupational health and safety requirement.

This theme emerged when Teams A and B were required to provide a collective statement on what they perceived as the specific need emanating from the empathy map presented in Theme 1, as well as insight into why the need exists. Teams A and B shared similar views, whereby their focus points included dose recording, occupational safety requirements and radiation risks, as evident from the following narrations recorded in the field notes:

Pregnant radiographers need a way to record dose readings because it is a legal requirement for future reference and peace of mind. (Team A)

A pregnant radiographer need[s] to monitor radiation dose exposure throughout pregnancy because of the fetus'[s] risk to (sic) *radiation.* (Team B)

During the analysis process, the two perceptions were merged to formulate a single point-of-view statement that guided the creation of the artefact.

Point of View statement

Pregnant radiographers ***(users)*** *need a method of monitoring and recording radiation doses throughout their pregnancies* ***(need)*** *because of the risk of radiation to their fetuses' and legal requirements for future reference, as well as peace of mind* ***(insight).***

Theme 3: Co-designing of the prototype mobile application: *PregiDose*

For this theme, Teams A and B merged; all participants provided verbal input, which was captured by the *Figma* facilitator and inserted into the *Figma* tool to create real-time screens (Figure 6). Epis et al. (2016) suggest that using technology as a means of input has the same accuracy rate as paper-based methods. Traditional wireframes use paper-based methods to sketch layouts and links (Epis et al., 2016). However, the *Figma* tool enables individuals to perform the same task while bringing their ideas to life in real time. The look and feel of the prototype were first established, with participants choosing the layout and template, as well as the name of the mobile application, *PregiDose* (see Figure 6 [a]). Participants emphasised the humanistic feel the mobile application should deliver to pregnant radiographers by including many features providing words of encouragement and support, as seen in Figure 6 (b).

The main objective of the mobile application, as relates to the POV statement described in Theme 2, is to monitor fetal radiation dose. Therefore, the core functionality of the mobile application is to enable the user to input daily readings. The participants recommended an *Upload Radiation Dose* link, enabling the user to input using various methods, as seen in Figure 6(e). Participants also included monitoring of radiation doses through a *View Radiation Dose History* link, whereby a record of daily to cumulative doses could be accessed, as seen in Figure 6 (f). The participants further advised on the need to share these results through various mediums such that the record can be easily accessible to their line managers, as visualised in Figure 6 (g). The participants were very thorough in addressing the educational needs of the pregnant radiographer by recommending training and information on the dosimeter through a *Search for Information and Videos* link, as seen in Figure 6 (d). This opened links to guidelines and regulations for pregnant radiographers, as well as *Frequently Asked Questions* and instructional videos on how to operate the fetal dosimeter. Participants further addressed the emotional needs of the pregnant radiographer by including features such as *Self-Care* (Figure 6h) and *Find a Friend*.

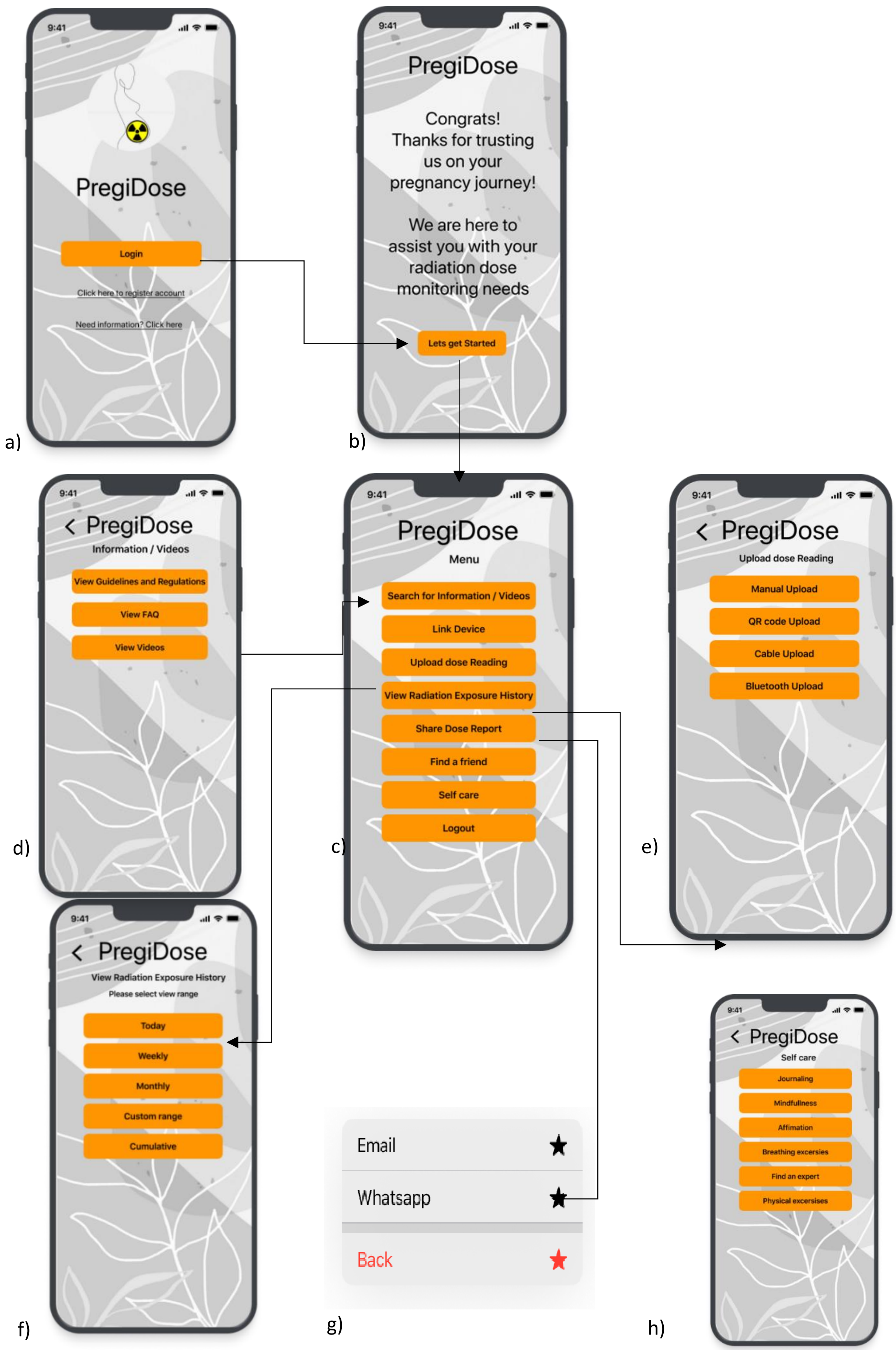

Figure 6: Flow diagram of participants' inputs with co-designing of the prototype mobile application using *FIGMA* screens.

Below is a discussion of the results of the design thinking process in relation to the prototype mo application designed by the participants.

Discussion

The design thinking approach has been widely and successfully used in the development of mobile applications (Suzianti et al., 2020; Petersen & Henpler, 2017; De Paula et al., 2014). This is attributed to its user-centric approach and the opportunity for participants to unlock their creative potential in solving problems (De Paula et al., 2014). In this study, the prototype mobile application was primarily guided by the empathy step, which revealed that pregnant radiographers have many pain points, such as fear and unsafe working environments. Pregnant women, in general, often experience anxiety and fear because of their unique physiological states (Grant & Erickson, 2022). However, pregnant personnel practising in ionising radiation environments have heightened fears due to the risk of fetal defects from radiation (Cheney et al., 2021). Vu and Elder (2013) state that this fear is unjustly exaggerated. The IAEA and ICRP further confirm that pregnant radiation workers are safe to practise, provided fetal doses are accurately estimated and remain below threshold limits (ICRP, 2001; IAEA, 2022).

In this study, the users described their concerns as unsafe environments and a lack of knowledge about their right to access fetal dosimeters. The absence of fetal dosimeters prevents the pregnant radiographer from measuring real-time fetal doses, which negatively impacts her ability to estimate threshold limits accurately, as required by the ICRP. Therefore, the prototype was designed such that the pregnant radiographer can access resources, like policies, regulations and guidelines specific to the country, thereby ensuring her understanding of her right to access a fetal dosimeter.

The core functionality of the mobile application is addressing the ICRP requirement of "accurately estimated" fetal doses below the threshold limit (ICRP, 2001). In the prototype, several features ensure that the pregnant radiographer can input radiation doses from the dosimeter to the mobile application, as well as view and share radiation doses, such that she can closely monitor her fetal doses at all times. Studies on real-time visual dosimeters allude to increased radiation protection measures by personnel aware of their doses (Butcher et al., 2015; Qureshi et al., 2022).

However, for the radiation dose inputs to be accurate, the user must be compliant and knowledgeable regarding the dosimeter. A study by Lee et al. (2022) reveals an underestimation of radiation doses captured on the National Dose Register (NRD) in Korea due to non-compliance with correctly and consistently wearing dosimeters by healthcare professionals working in fluoroscopy-guided interventional theatres. Similarly, if pregnant radiographers do not wear the fetal dosimeter correctly or set appropriate dose limits, the input data in the mobile application would be incorrect and potentially hazardous. To mitigate this challenge, participants included a *View Video* link in the *Search for Information* link to provide instructional videos on how to use the fetal dosimeter. Lastly, participants underscored the reality of the pregnant radiographer being a pregnant woman first and foremost. Although this was not the core functionality of the mobile application, participants prioritised the mental and physical health of the mother towards maintaining a healthy pregnancy. The *Self-Care* feature addressed these needs.

Conclusion

In this study, a prototype mobile application for fetal dose monitoring was co-designed through a creative process facilitated by the design thinking approach. The prototype encompasses several features that focus on the core functionality of fetal radiation dose monitoring, which envisions improving radiation protection measures for pregnant radiographers and their unborn children. In addition, the lessons learnt from the empathy phase further support education and wellness links that surpass merely addressing the occupational health and safety needs of the pregnant radiographer and instead would also support the mental health and wellness of a pregnant woman. Hence, these considerations will be used as an essential framework to guide the development phase of the final artefact.

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Conflict of Interest
None

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4.1.3 Manuscript 4

In Manuscript 3, a prototype mobile application was developed through a user-centred approach. Manuscript 4 presents the development processes undertaken by software developers to produce and test the final mobile application in a controlled environment. This manuscript addresses Objective 3 (Development Cycle 2), which is developing a prototype of the mobile application based on the suggestion.

Thus, the manuscript provides a technical report and is currently under review in the *Journal of Medical Internet Research* (JMIR) research protocols.

Implementation of a mobile application development model towards PregiDose: A fetal dose tracking app for pregnant radiographers.

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1. INTRODUCTION

The adoption of mobile applications facilitated through smartphones is rapidly growing due to the ease of access to smartphones and the dependence of humans on technology (Etim et al., 2020; Liu et al., 2018). Mobile applications have the ability to support human needs through the monitoring of daily activities (Daly et al., 2018). There is a growing emphasis on individual health surveillance towards preventive healthcare. The regular interaction with one's own data enables users to identify trends and early health warning signs. This facilitates proactive interventions towards preventing severe health conditions. Coupled with the widespread availability of smartphones in both developing and first-world countries, mobile applications are, therefore, at the centre of successful technology adoption (Etim et al., 2020).

Pregnant women, in particular, are moving towards the use of technology as a means of support through their pregnancy (Daly et al., 2018). Lupton and Pedersen (2016) described three main categories of pregnancy applications, namely 1) entertainment, 2) self-monitoring and 3) pregnancy education. These categories enable pregnant women to monitor their health and that of the fetus closely, as well as to gain knowledge and understanding of the different stages of the pregnancy. These factors contribute towards reassuring the mother of the unborn child's health and well-being (Lupton & Pedersen, 2016). The World Health Organization (WHO) places great importance on the good health and well-being of individuals, which is highly regarded as Sustainable Development Goal (SDG) 13. Pregnant women undergo sematic, physiological and emotional changes during pregnancy, which often increase their stress levels, negatively impacting the fetus (Bjelica et al., 2018). Maternal health, as described by the WHO, is the good health and well-being of the women during their pregnancy, whereby each stage is a positive experience enabling both mother and child to thrive (WHO, 2023).

Pregnant radiation workers work in ionising radiation environments, which can be potentially harmful to the developing fetus. Various levels of radiation exposure have the ability to cause damage to cells and tissues and can be classified as deterministic or stochastic (Sherer et al., 2017). Deterministic effects are a result of excessively high radiation exposures (Sherer et al., 2017). The effects of high radiation doses on a fetus were documented through the Chernobyl and Fukushima events. Exposures exceeding 100 mSv resulted in pregnancy loss, malformations, neurobehavioral abnormalities, fetal growth retardation, and cancer (Fushiki, 2013). However, stochastic effects include non-specific, non-predictable effects that can result in the alternation of DNA, leading to genetic mutations or cancer (Sherer et al., 2017). For a pregnant woman, both types of effects can evoke fear and anxiety, particularly stochastic effects, which is a developing research area (Applegate et al., 2021). The fear of radiation itself has the potential to threaten the health and well-being of the fetus through maternal stressors from the mother (Fu et al., 2023).

Occupational health and safety regulations for pregnant radiographers include wearing a fetal dosimeter and recording fetal exposures (ICRP, 2000). The International Commission for Radiological Protection recommends a threshold limit of 2 mSv, which is considered safe with negligible effects on the fetus (ICRP, 2000). Therefore, it is the responsibility of the radiation worker to ensure that the dose does not exceed the threshold limit through daily monitoring of the fetal exposure. However, a study by Essop et al. (2023) revealed that uptake of these recording and monitoring measures remains low. Therefore, it is evident that pregnant radiation workers are a vulnerable group of pregnant women who have specific requirements over and above that of pregnant women.

Mobile applications for pregnant women are widely available; however, in light of the gap in the literature, it is evident that there was a need to harness technology to provide a tailored intervention towards inconsistent fetal dose monitoring. The researchers then developed a mobile application called *PregiDose*. Therefore, the scope of this paper is to present the application of an intricate mobile application development model towards developing *PregiDose*. The paper further describes the mobile application features and their significance in addressing radiation protection for pregnant radiographers.

2. METHODS

The mobile application underwent two development cycles. The first included a situational analysis and prototyping of the research idea through a user-centred design approach. The second cycle included the final mobile application development of the artefact, which is presented in the subsequent sections. Several mobile application development models can be adopted for producing an artefact (Jabangwe et al., 2018). Most development models commonly include eight areas described in Sommerville, namely 1) Project Management and Planning, 2) Requirements, 3) Design, 4) Coding 5) Testing, 6) Deployment, 7) Maintenance, and 8) Project Evaluation (Vithani & Kumar, 2014). Vithani and Kumar (2014) describe a similar model for the mobile application development life-cyle (MADL); however, theirs encompasses seven steps, namely 1) identification, 2) design, 3) development, 4) prototyping,5) testing, 6) deployment and 7) maintenance. In this study, Vithani and Kumar's (2014) model was adopted as the overarching theoretical framework for the development processes. The rationale for this selection was that this phase required an initial prototype to gain the client's feedback. The development processes were executed by software engineers in South Africa. The team consisted of a project/account manager, a UX designer, a UI/ UX designer, two *Flutter* developers, and a test analyst. A *Flutter* framework was used to build the mobile application. *Flutter* is a framework by Google for building beautiful, natively compiled, multi-platform applications from a single codebase. The entire development process was executed over five months (August 2023 to January 2024) The processes and outcomes for each step are described in Section 3.

Ethical consideration and copyright

The study gained ethical approval from the research ethics committee of the Faculty of Health Care Sciences, University of Pretoria (632/2021). Prior to the development of the mobile application, the researchers engaged with the University's Information Protection (IP) department to ensure that no other mobile application existed with the same name and content. The researchers then gained the copyright to the name *PregiDose* and its logo.

3. RESULTS

The mobile application development lifecycle methodology was applied and resulted in the following outcome:

3.1 Identification

This phase involves understanding the client's requirements, setting project goals, and outlining the project scope (Vithani & Kumar, 2014). In this study, a face-to-face discussion with the researcher and development team took place to understand the prototype requirements from Cycle 1. This included narrowing down the most important and feasible core functionalities that were created on *Figma* screens during Cycle 1. Three categories were established as core functional areas of the app, namely 1) Dose-Tracking, 2) Journaling, and 3) Explore, whereby each category expands into various other features.

3.2 Design

This step involves the developers creating the software architecture for the mobile app, as well as determining feasible and suitable platforms to host the app (Sommerville, 2011). For this study, the team developed a modular and scalable architecture for the app. This involved choosing appropriate design patterns and deciding on the tech stack that included *Flutter*, *Dart*, and various *Flutter*-

compatible libraries. Storyboarding and *Figma*: The UI/UX designers created a storyboard to visualise the user journey. They used *Figma* for interaction and visual design, creating wireframes, mockups, and prototypes to obtain a clear picture of the final product. The mobile application was developed to operate on the Android operating system only due to time and financial constraints associated with expanding the host platforms.

3.3 Development

The application was coded in this step. This can take place in two steps, whereby the core functionalities are coded first, followed by the user interface (UI) design (Vithani & Kumar, 2014). Back-end (or server-side) logic was developed in parallel with the front-end (or user interface). The back end was developed using *Node.js*, while the front end was developed using *Flutter*. *Node.js* is an open-source, cross-platform, *JavaScript* runtime environment that executes *JavaScript* code outside a web browser. It enables developers to use *JavaScript* to write command-line tools and for server-side scripting—running scripts server-side to produce dynamic web page content before the page is sent to the user's web browser. This is an important step towards ensuring that the mobile application can function across a range of mobile operating system platforms. The developers wrote the code in *Dart* using the *Flutter* framework. They focused on implementing features as per the design, ensuring responsiveness and smooth user experience. Early versions of the app were tested internally for basic functionalities.

3.4 Prototyping

In this step, the functional requirement of each category was analysed and sent to the client for verification. It is a continuous back-and-forth process between the design team and the client until the final prototype is ready (Vithani & Kumar, 2014). In this study, the mobile app developers hosted a virtual demo and feedback session of the prototype (Figure 1). This phase was crucial for understanding the client's perspective and making the necessary adjustments. At this point, the look and feel of the app were amended to make it aesthetically appealing to the target audience of pregnant women. The logo was also amended from an abstract view to a more direct feminine view of pregnancy. Core functionalities were also reconsidered, with secondary features for sharing dose reports being recommended.

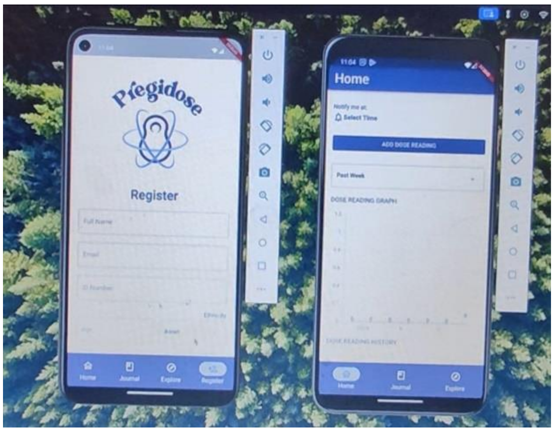


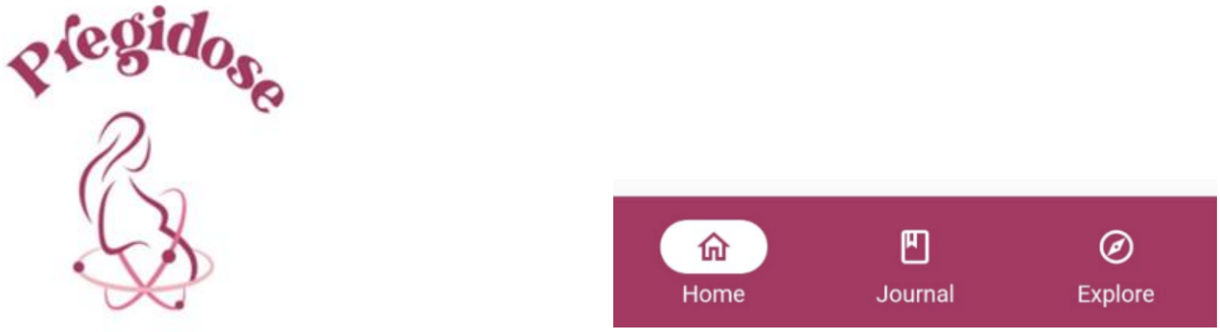
Figure 1: Virtual demo and client feedback session with prototype of the mobile application

3.5 Testing

Testing is an essential aspect of quality assurance in the development process (Sommerville, 2011), as well as ascertaining the usability of the mobile app (Weichbroth, 2020). The test analyst rigorously tested the app for various parameters like functionality, usability, performance, and security. They used both automated and manual testing methods. Bug-fixing was also employed to identify bugs, which were then reported back to the development team for fixes.

3.6 Deployment

This is the final phase of the development process following the testing of the prototype. In this study, adjustments from the feedback session were implemented regarding the look and feel of the app, as well as other minor amendments (Figure 2a). The final Android Package Kit (APK) file was then released. Pregnant radiographers interested in the study were then required to complete a registration form for the client to capture their initial details onto the app registration platform. The team further developed a *PregiDose* User Registration manual to assist the users in completing detailed information on the self-registration landing page. The app was then used in the real-life clinical setting by the pregnant radiographers. The final app comprised three core functional areas, namely Home (Dose-Tracker), Journal and Explore (Figure 2b).



a) b)

Figure 2: a) Final mobile application logo and b) core functional areas

The dose-tracking functionality (Figure 3a) is one of the main features of the app, as it directly addresses the research problem of inconsistent dose-tracking methods by pregnant radiographers. Here, pregnant radiographers are able to input their daily fetal doses acquired from the dosimeter (Figure 3a). Additional verification features, such as taking a picture of the dosimeter reading, as well as sharing the dose report, were included to enhance fetal dose tracking. The dose inputs are translated into a graph, whereby the pregnant radiographers could have a visual representation of the accumulative doses (Figure 3b).

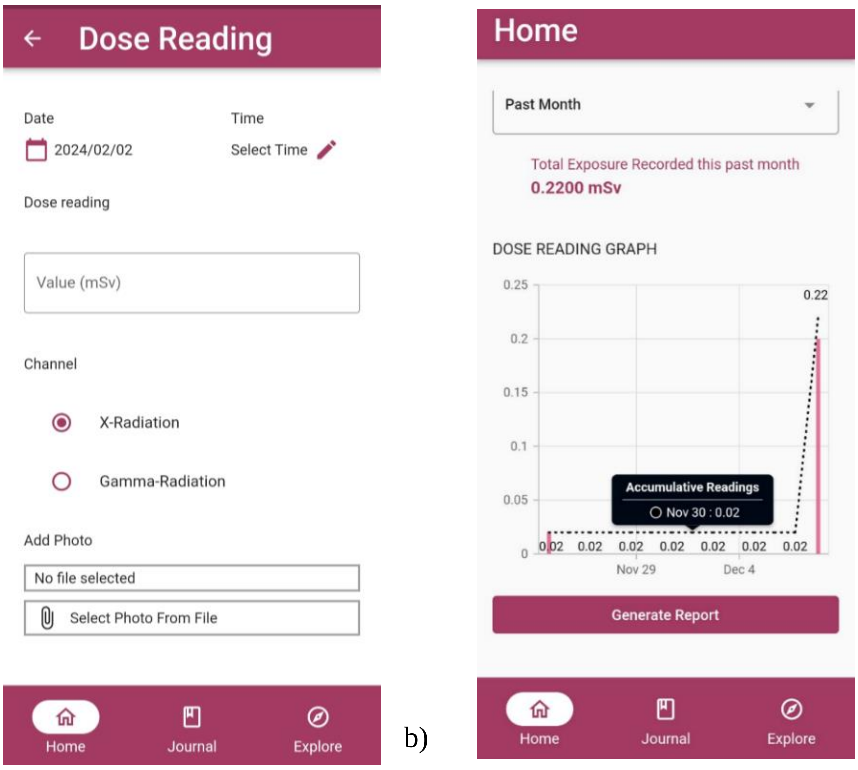


Figure 3. Dose-tracking feature

The Explore function (Figure 4) expands into pregnant radiographer wellness and support features, including access to radiation safety guidelines, mindfulness practices and social support networks (Figure B). Radiation safety guidelines included both international and national policies for pregnant radiographers recommended by the ICRP, IAEA and South African Health Products Regulatory Authority (SAHPRA). Links to mindful practices for pregnant radiographers specifically were included. Social support networks offered by the app included a link to a social media group of other *PregiDose* users. Lastly, the Find an Expert feature enables pregnant radiographers to connect with experts to offer technical support with the app and dosimeter.

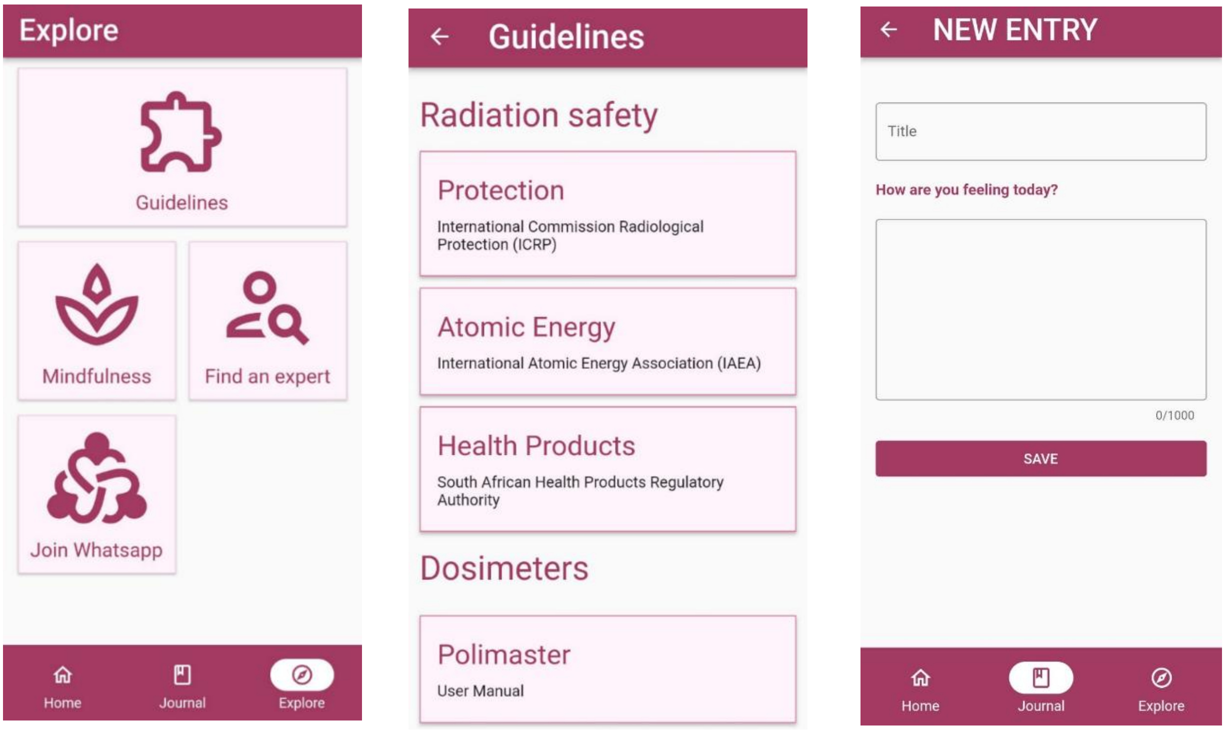


Figure 4: Explore features and sub-links to guidelines and journaling.

3.7 Maintenance

This is the final stage of the model and is an ongoing process between the user, client and developers. This stage offers further support to the end users, whereby the developing team remain on standby to respond to any performance issues reported by users. In this study, the team worked on updating the app and fixing bugs based on feedback to enhance the overall user experience and ensure all features were functioning as expected. Participants using Samsung handheld devices encountered challenges with firewall protection preventing the app from being installed. The team then developed an installation user guide, which provided detailed steps on how to download the file. Vithani and Kumar (2014) also describe this phase as a marketing opportunity whereby the app's unique features are marketed. For *PregiDose*, a promotional video was also created by the design team, showcasing the app's highlights (Essop, 2023).

Discussion

In this study, the application of the mobile application development processes within the model was implemented to create *PregiDose*. Jabangwe et al. (2018) emphasise the importance of adopting an effective development model such that it can serve as a successful high-end mobile application in the context of competitive mobile app development. This is especially significant in the research context, which is focused on creating theories, modelling frameworks and constructing methods for mobile applications in various settings (Weichbroth, 2020).

In the context of occupational radiation safety for pregnant radiographers, the mobile application serves as a central hub for inputting daily dose recordings and storing and sharing the results. Therefore, this feature addresses the ICRP recommendation for effective dose estimates to ensure that the fetal dose does not exceed a threshold of 2 mSv (ICRP, 2000). The graph functionality enables pregnant radiographers to monitor their readings closely and detect elevated levels of radiation exposure. This is an important feature for radiation protection, such that the pregnant radiographer can increase her radiation safety vigilance. The International Atomic Energy Association (IAEA) suggests that a pregnant radiographer could request to change her position to an area that might have a lower ambient exposure and reduced scatter radiation (IAEA, 2022). Nuclear medicine radiographers could observe stricter measures, particularly when spending a great deal of time in radiopharmacy or working with radioiodine solutions (IAEA, 2022). Radiation therapy radiographers working in high radiation dose environments and handling sealed sources might also opt not to work in manual brachytherapy. The IAEA (2022) further recommends employees evaluate their work environment to ensure that the probability of high radiation dose accidents remains low. Therefore, the mobile application—in the context of occupational radiation safety—serves as a preventative measure towards mitigating further radiation exposure that can contribute to stochastic effects, and in high radiation dose accidents, deterministic effects (Applegate et al., 2021).

The second core functionality of the mobile application expanded into several other features aimed at supporting mental and emotional well-being, as mentioned in Section 3.6. The first feature includes guidelines for radiation protection. In this era of technology, more people are turning to online resources as a primary route to health information (Ziebland & Wyke, 2012). Previously, policies based on scientific information were difficult to comprehend, often deterring the public from engaging with them (Ziebland & Wyke, 2012). Similarly, literature on radiation effects on the fetus is widely available; however, a study by Essop et al. (2023) identified that pregnant radiographers may lack education and training on the fetal dosimeter owing to its low utilisation. In this study, easily understandable pregnancy radiation protection guidelines were included, offering appropriate, factual and nonthreatening information for pregnant radiographers. Engaging with and understanding these resources are essential for improving their knowledge and, thus, compliance with radiation safety measures.

Pregnant women are considered a vulnerable group because of their altered physiological states (Blehar et al., 2013). They often require increased emotional and mental support to ensure the well-being of their unborn child. Support features in the app include links to mindfulness and social connection. Mindfulness is a form of psychotherapy that can be used to alleviate anxiety and depression (Chen et al., 2023). Chen et al. (2023) describe mobile mindfulness meditation (MMM) as a mindful practice facilitated through a mobile device or app instead of contact interaction. The reported advantages of this include accessibility, no costs and privacy. As described in Section 3.6, social networks facilitated through the app include links to pregnancy social media groups and radiation experts. Social connection for pregnant women is one of the social determinants of maternal health that is proven to have a positive effect on neonatal outcomes (Manzar, 2022). Zeibland and Wyke (2012) explain that sharing challenges in an online environment can serve as an emotional outlet, whereby similar problems are now perceived as normal, enabling the individual to cope better in the real world. In this study, pregnant radiographers could connect and share anxieties and fears associated with radiation, among other challenges. Connecting with an expert further enables them to obtain professional advice by enabling them to seek guidance and clarity on any concerns regarding radiation and dosimetry.

Lastly, the concept of journaling was added as another emotional support feature. The practice of journaling is a form of psychotherapy which incorporates expressive writing over consecutive days for 20 minutes (Sohal et al., 2022). This exercise was noted to be more successful in women than men in relieving anxiety and depression (Sohal et al., 2022). In the context of the study population, pregnant women working in high-risk environments could benefit from this feature.

Conclusion

PregiDose is an innovative mobile application developed through a rigorous process model aimed at ensuring high quality. The app focuses on supporting radiation safety requirements set by international radiation protection bodies, particularly in the context of fetal dosimetry. By doing so, it serves as a valuable occupational health and safety tool. Moreover, *PregiDose* incorporates features designed to provide mental and emotional support, aligning with the World Health Organization's Sustainable Development Goal 3, which targets good health and well-being, especially for maternal and fetal health.

The development of *PregiDose* involved a transdisciplinary collaboration between radiographic sciences and information technology, which underscores its contribution to Sustainable Development Goal 17, emphasising partnerships for achieving common goals. In summary, *PregiDose* represents a significant technical innovation that addresses critical health and safety concerns for pregnant radiographers while also contributing to broader sustainable development objectives.

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Conflict of Interest

None

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4.2 Chapter 4 Conclusion

This chapter elaborated on the development processes that informed Cycles 1 and 2. In Cycle 1, a prototype was developed through a user-centred approach. A design thinking methodology was used to facilitate the BUS conceptual framework. In Cycle 2, the MADL methodology was used to create the final artefact and also test the app for its useability before launching it in a real-life setting. The app was then evaluated for its usefulness, which is presented in the next chapter.

CHAPTER 5: EVALUATION OF THE MOBILE APPLICATION – DSR STEP FOUR

5.1 Introduction

Chapter 4 elaborated on the development process for the design and development. *PregiDose*, a mobile application for pregnant radiographers, was the end product of these processes. Chapter 5 presents the evaluation of the app, which addresses objective 4 of the study which is, to determine the usability and usefulness of the mobile app for fetal dose recording, monitoring and education. In this chapter, the researcher presents the views of the pregnant radiographers who had engaged with the app in a real-life setting and provided feedback on their experiences. These findings are presented in Manuscript 5 below, which is still in a draft format. The manuscript follows the guidelines outlined by the *International Journal of Medical Informatics*.

5.1.1 Manuscript 5

Perceptions of pregnant radiographers regarding the usefulness and usability of *PregiDose*. A mobile application to enhance fetal dosimetry and well-being.

H.Essop,[a] M. Kekana,[b] and H Smuts[c]

1. INTRODUCTION

The uptake and growth of mHealth apps have increased rapidly in recent years; however, continued usage past the initial phase has been limited (Vaghefi & Tulu, 2019). Therefore, usefulness and usability testing are essential aspects of successful mHealth applications. Several pregnancy apps are available to pregnant women, offering a wide variety of health screening and monitoring in pregnancy that support both mother and child (Daly et al., 2018).

However, pregnant radiographers remain radiation workers who work in ionising radiation environments. The health and safety requirements related to pregnant radiographers differ significantly from the general population of pregnant women. High radiation exposure to the fetus can contribute to deterministic effects such as congenital malformations, mental retardation, and microcephaly, among others (Brent, 2015). Nevertheless, occupational exposures are unlikely ever to yield detrimental dosage levels to the pregnant radiographer (Ulanowski et al., 2019). Therefore, the area of concern and fear resides in the uncertainty associated with stochastic effects. Stochastic effects are non-probable and do not depend on a specific threshold limit (Choudhary, 2018). These effects have the potential to cause spontaneously induced cancer. Nevertheless, Doll and Wakeforward (1997) maintain that in-utero radiation is a causative factor for inducing childhood cancer, even at low doses such as 10mGy. Hence, screening and dose recording become an integral aspect of pregnant radiographers' lives, requiring daily monitoring. The International Commission for Radiological Protection (ICRP) recommend a threshold of 1 mSv, which should be measured effectively and accurately to ensure the safety of a pregnant radiographer's fetus.

PregiDose is an mHealth application that was tailored to address the needs of pregnant radiographers in terms of effective dose tracking. Given the health risks associated with radiation dose exposure, it could be presumed that this task would be executed consistently. However, Essop et al. (2023) identified several deficiencies in this area, which could be addressed with a mobile app. Accordingly, the app was developed to effect certain behavioural changes. This practice can only be achieved with continued use and engagement with the app and a subsequent evaluation of the user experience. Usefulness testing evaluates participants' experiences and satisfaction with the app, whereas useability reflects on the technical aspects of the app that enable users to engage effectively with it (Muhamat et al., 2021). The useability of the app can also be equated with it's ease of use[20].

Therefore, this paper aims to evaluate the usefulness and useability of *PregiDose* as perceived by the users.

2. METHODOLOGY

The study adopted a qualitative design with an exploratory and descriptive approach. Denisson et al [21] suggests that there are limited qualitative research exploring the experiences and views of end users of mobile apps. Therefore, there is a need to gain a deeper understanding into user experiences that can support behavior changes that contribute to motivation an interest in continued use. This can be applied to both usefulness and usability testing, where the apps ease of use is described by the user[20]. The study population included all pregnant radiographers who worked in diagnostic, radiation therapy and nuclear medicine departments. The exclusion criteria were pregnant radiographers using iOS mobile devices, which were not yet supported on the mobile application platform.

2.1 Recruitment and sampling

The participants were recruited using a purposive sampling method, whereby the database from the situational analysis phase of the study was accessed. In DSR Step 2, women were given the opportunity to provide details to engage with the app in the event that they would be pregnant during the time of development completion. The second recruitment and sampling included the snowballing method, whereby the researcher sent out an invitation link (Appendix J) (https://forms.gle/dh8hCGicDJEqSeuS7) to her professional circle and heads of departments in each clinical training setting. Lastly, the invitation was also shared on radiography-specific social media platforms such as *Locum Radiographers SA*, as well as the researcher's professional social media LinkedIn and Facebook accounts. The invitation link provided an overview of the study and served as informed consent upon completion. This invitation also required the contact details of the participants and the types of phones they used—to screen for eligible participants.

2.2 Data collection

Suitable participants were registered on the app, and an information package, including guidelines on the use of *PregiDose* (Appendix K), the ethics certificate (Appendix F), and the APK file, were then emailed to the participants. Subsequently, the participants could engage with the app in a real-life setting from October 2023 to March 2024. Thereafter, they were invited to a telephonic interview to share their experiences. Seventeen pregnant radiographers responded to the invitation and shared their details for registration. However, 10 pregnant radiographers actually engaged with the app and only four responded to the interview invitation (Appendix L). Guest et al[22] explain samples sizes in qualitative data collection methods may differ. Smaller number of participants may still yield sufficient results which can be used to create themes, depending on the quality of the interviews and richness of data[22]. The anonymised database can be accessed in Appendix M. The telephonic interviews were guided by a semi-structured interview guide (Appendix O), which allowed for probing questions. The interviews were recorded with a voice recorder and transcribed using AI-powered software, *Transkriptor*. The researcher evaluated the transcription to ensure accuracy and constancy in relation to the audio. The analysis was verified by the co-authors to ensure the validity and reliability of the results.

2.3 Ethical consideration

The study gained ethical approval from the Faculty of Health Care Sciences, University of Pretoria, Research Ethics Committee (613/2021) (Appendix G). The participants' autonomy was maintained by informing the participants that they could withdraw from the study at any time. This included both the engagement with the app and being interviewed on their feedback. In this study, it was observed that most of the participants preferred to use the app; however, only a limited number responded to the follow-up interview invitation. Non-maleficence was maintained by ensuring that the pregnant radiographers continued to use their original, traditional methods of dose tracking in conjunction with the app, as the app is still in its testing phases of useability and usefulness (Appendix H).

3. DATA ANALYSIS

The verbatim transcripts were analysed using reflective thematic analysis (RTA) described by Braun and Clark (2022). This six-phase analytical process includes 1) familiarisation with the data, 2) generating initial codes, 3) generating themes, 4) reviewing potential themes, 5) defining and naming the theme, and 6) producing the report. Braun and Clark (2022) explain that RTA is about the researcher's reflective and thoughtful engagement with their data and the analytical process (Byrne, 2022). In this study, the researcher applied the RTA steps by immersing herself in the data and identifying common patterns that served as codes. The responses were further labelled as either positive, neutral or negative (Wang et al., 2018). Step 3 followed a deductive and inductive approach, whereby the researcher revisited the data backwards and forwards. In the deductive approach, hypothesised themes were already in place and were based on the researcher's prior knowledge and existing theory (Proudfoot, 2023). These include the core functionalities of the mobile app features, namely dose tracking, education, journaling and mindfulness, upon which the participants needed to reflect. However, in this study, an inductive approach was also necessary to generate new themes from the data. In Step 4, the themes were analysed and dissolved into each other if similarities were found. In Step 5, four overarching themes were defined, namely 1) Usefulness of *PregiDose*, 2) Useability of *PregiDose*, 3) Barriers to *PregiDose* Adoption and Utilisation, and 4) Recommendations for the Advancement of *PregiDose*. The next section of this paper presents the final report, with supporting narrations.

4. RESULTS

Table 1 provides an overview of the codes and themes generated through the RTA process. Excerpts of the raw data can be viewed in Appendix O.

Table 1: Application of the RTA to the generation of final themes.

CODES	FINAL THEMES
Experiences with Dose-Tracking feature	1. Usefulness of the mobile app (Deductive analysis)
Experiences with Education links	
Experiences with Journalling and mindfulness features	
Ease of use	2. Useability of the mobile app (Inductive analysis)
Accumulative dose	
Dose capturing	
Time constraints	3. Barriers to adoption (Inductive analysis)
Physiological and sematic conditions of pregnancy	
Lack of persuasiveness	
Notifications	4. Recommendations for mobile app advancement (Inductive analysis)
Interest	
Automation - the use of the mobile device as a dosimeter	

The upcoming sections elaborate on the themes with literature control. Individual participant responses were anonymised and demarcated as P1, P2 and P3.

Usefulness of PregiDose

Section 3 stated that the study initially used a deductive approach to analyse the data. Accordingly, three sub-themes were hypothesised based on the core functionalities of the mobile application. Hence, the participants were asked how they had experienced these functionalities to assess the usefulness of the app in the real-life setting. The participants' responses were labelled as positive, since they found the app beneficial, as described in the following narrations:

"It was very useful." [P2]

"It was useful especially to see the chart." [P?]

"I like the fact that we can see the chart [Figure 1] *and the accumulated doses. Usually in the department we have a paper that we had to write the doses on, it's a very old school way of doing it"* [P4]

They further indicated that the educational features were helpful, with statements such as "*It was very nice*" [P1] and *"It was informative"* [P3]. The participants indicated that although they did not actively engage with the journaling feature, they found it potentially useful, as stated in the following narration:

"Radiographers we go through the most, especially with our work. So, we just kept telling our feelings there [journal], *how the day went, and how the work as a whole is going, as a radiographer."*[P2]

Other participants indicated that they had never practised manual journaling before and found it difficult to adopt, as indicated in this statement:

"*I haven't used it, I know some of my colleagues said they wished they had a journaling feature and write down how they were feeling, but I'm not a big journal user, so for me it was not my thing".* [P4]

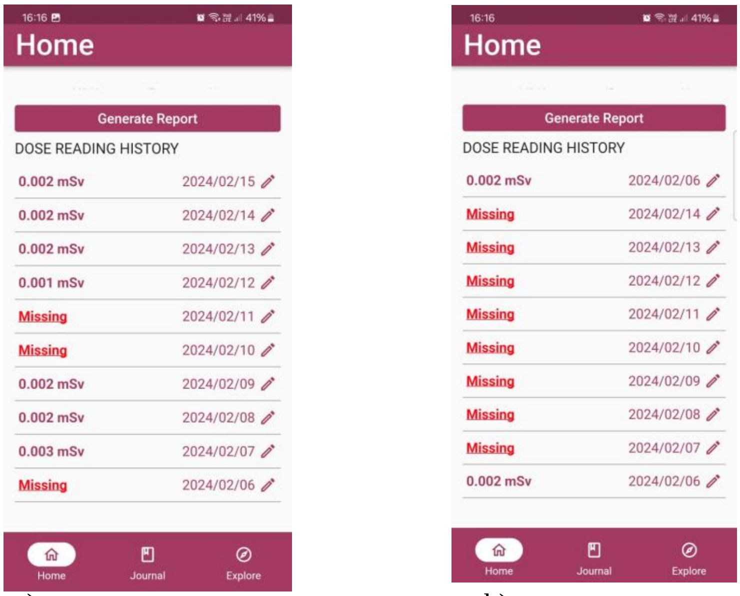
Some participants who had indeed engaged with the mindfulness features had labelled it positive, as described in the following narrative:

"*I think it's very nice to have some information about other stuff that you can do.*"[P1]

Useability of PregiDose

The technical aspects of the mobile app are an indicator of the useability of the app. The participants had a positive view of downloading and using the app, as indicated in the following narration: "*It was quite simple."* [P1]. Consequently, its ease of use and simplicity are positive indicators of the useability of the app. However, participants described some technical aspects that hindered the app's accuracy regarding the accumulative dose and data capturing using the camera. A participant shared real-time screenshots of these challenges to support her contention.

"*Here are some of the screen shots of the missing readings. So sometimes it shows as many missing readings, and if I say go to the journal and back it will only be the two or three readings missing.*" (Figure 1a) "*But if I edit the reading, others go missing again.*" (Figure 1b) [P1]



a) b)

Figure 1: a) Original dates of missing records b) Existing entries missing after adding missed dates.

The participant also reported challenges when trying to capture the data from her dosimeter using the camera function; however, the participant discovered alternate ways to overcome the problem, as reflected in the following narrations and supporting screenshots (Figure 2):

"The bottom icons are in the way and I am unable to take a pic. So have to take it beforehand and then upload it." [P3]

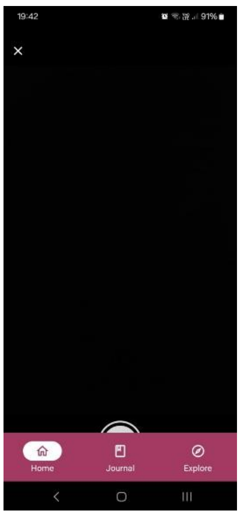


Figure 2: Screenshot to visualise the journaling icon hindering the camera function.

These findings suggest the dose-tracking feature worked effectively, provided the readings were consistently recorded. However, the accuracy of the recorded information was compromised when the participants did not input their doses on a particular day. Therefore, this finding is labelled negative and requires improvement.

Barriers to the adoption of PregiDose

In this theme, several barriers apparently having a negative influence on the user's adoption and usage of the app emerged, including physiological and motivational barriers and time constraints. The participants indicated they were tired and forgetful, which resulted in them not engaging with the wellness support features of the app. This was described in the following narrative, whereby participants stated:

"*We get tired also.*" [P2]

"*My pregnancy brain, it's just so difficult to remember.*" [P1]

In keeping with the support features, many participants indicated they "*Didn't see that*" [mindfulness] [P2] and "*Didn't view that*" [mindfulness] (P3). This might be attributed to a lack of motivation or the persuasive nature of this feature.

All participants indicated they were time-constrained with work responsibilities, which impacted their ability to engage with support features other than the primary dose recording function fully. This is described in the following narrations:

"The time slot that I use the app is, I put my reminder in for eight o'clock. That's when I get to work or I'm at work already for a while. So that's the time that I set out. There's not really much more time. And when you leave for work, you don't really think about the app anymore because I see it as a work function." [P3]

"*We can be very busy, so there's no time.*" [P2]

The participants then provided recommendations for the advancement of the mobile application based on their experiences of using it in a real-life setting.

Recommendations for the advancement of PregiDose

In this theme, the participants reflected on strategies that could improve the adoption and utilisation of the app. This included notifications, interest and automation.

In Theme 3, it was evident that the pregnant radiographers' physiological states can be attributed to radiographers not inputting their daily doses consistently. Consequently, the participants suggested having daily reminders from the app, as stated in the following narrative:

"*A notification on the phone where it reminds you to record your dose. It would be very helpful because it will remind us to insert our recording. If you don't record, it means you're not doing anything with the app.*" [P2]

Some participants also reported not seeing and engaging with the journaling and mindful features. In Theme 3, the participants indicated that they perceived the app as a work function and did not feel the need to use it after hours. Therefore, it is evident that pregnant radiographers require something that can stimulate their interest in using the app beyond its dose-tracking features. The participants suggested the following:

"*I think something that a lot of people would like to engage with is maybe some weekly information about your baby.*" [P1]

"I think maybe some articles, like I am eight weeks, maybe something that tells you that this is week eight, these are the things that will be happening, maybe baby is developing this and that." [P4]

Given the barriers described in Theme 3, the interviewer probed further on strategies that could be useful for ensuring consistent dose inputting. This included automatised dose recording, whereby the mobile device itself could be used as a dosimeter. The participants responded positively, as evidenced by the following narrations:

"*I think it would be very great. It would be a very useful feature because now, like our phones, we have our phones everywhere we go, everywhere in the department, wherever we go. So sometimes they say, okay, we are supposed to wear our dosimeters wherever we go and every day, but I feel like a phone is more, compared to a dosimeter, I feel like a phone is much better. You look for your phone, not your dosimeter first.*" [P2]

"*Yeah. I think so because now you're walking around with a bag all day with your cellphone, your dosimeter, your other dosimeter, your name tag. So now it would be nice if your cellphone could you replace at least the two dosimeters.*" [P3]

"It would be cool if you could connect the dosimeter to the app, like an automated thing." [P4]

These views describe the need for automation if the app were to be advanced.

The next section discusses each theme in relation to the literature.

5. DISCUSSION

Usefulness of PregiDose

The successful adoption of mobile apps depends on the perceived usefulness of the app in the user's daily life (Vaghefi & Tulu, 2019). Traditional methods of fetal dose tracking included writing doses in a logbook or data capture sheet provided by the employer [23]. The findings in this theme suggest that pregnant radiographers perceive this approach to dose tracking as aligned with the advancements of the technological era. In particular, the pregnant radiographers of this study found the dose-tracking feature and education links the most useful. Hughson et al explain that pregnant woman prefer using pregnancy apps that are relevant to their own health care context [24]. In this setting, the app was designed to cater for the needs of a pregnant radiographer working in an ionizing radiation environment. This presents a unique offering in the context of pregnancy apps for the pregnant radiographer. Responses to features that support mental well-being, such as journaling, were labelled as neutral, and mindfulness as positive. Pregnancy apps are fundamentally based on the idea of self-tracking [25]. However apps also have the potential to exploit confidential information about the user such as bodily functions, behaviours and social relationships [25]. The technical teams overseeing the backend operation of the app have access to this data and may have access to the information entered by the user. Journaling offers the user with a platform to share personal thoughts and feelings. Consequently, it is therefore understandable that they may not want to use the app for this function. The findings in this study indicate that the pregnant radiographers welcomed the concept of journaling, however their disengagement may indicate underlying apprehensions associated with factors described by Barassi [25].

Useability of PregiDose

Useability testing is an essential aspect of mobile app development to ensure an app is functional and user-friendly (Baharuddin, 2013). This testing occurs within the mobile app development lifecycle in a controlled environment with software developers using various handheld devices (Vithani & Kumar, 2014). These errors are corrected and retested before deployment. Useability testing thus continues naturally onto the deployment phase, whereby the app is tested in a real-life setting. Such testing offers valuable results as it is a direct indicator of user satisfaction and effectiveness, as experienced by the users themselves (Hoehle & Venkatesh, 2015). The core functionality of the app in this study is dose tracking and recording to enhance fetal dosimetry. The requirements for pregnant radiographers, as recommended by the ICRP, is ensuring doses can be measured accurately and effectively and fall within the recommended limit of one milli Sieverts (1 mSv) (ICRP, 2000). Thus, useability testing in the natural setting was necessary for improving the app.

Barriers to the adoption and utilisation of PregiDose

A radiography department often encounters high patient volumes and a consequent increased workload for radiographers (Robertson et al., 2022). Several studies report that radiographers generally suffer from physical and emotional burnout because of their highly stressful working environment (Alakhras et al., 2022). However, such physical and emotional exhaustion is heightened for pregnant radiographers due to the physiological and somatic changes associated with pregnancy and manifests in tiredness, slight dyspnoea and backache, among others (Sharma, 2015). Accordingly, the participants' responses confirm that pregnant radiographers might experience increased fatigue and thus have no energy and desire to interact with a work-related device. In addition to fatigue, the phenomenon of the 'pregnancy brain' also emerged. This term is adopted by the lay public to describe the common occurrence of memory lapses in pregnant women. This might be attributed to the pregnancy hormones remodelling the brain architecture and neural functioning (Brown & Schaffir, 2019). Thus, the phenomenon aligns with the participants not remembering the non-essential aspects of the mobile application.

Recommendations for the advancement of PregiDose.

The participants in the study recommended that strategies such as notifications, pregnancy information and automation could promote behaviour changes regarding the consistency of dose recording and engagement with the well-being features.

Notifications are described as alerts or reminders triggered by the app to remind the user to engage with the app for the intended health goal (Vaghefi & Tulu, 2019). Vaghefi and Tulu (2019) explain that some users perceive notifications as a distraction; however, other users, such as in this study, prefer frequent notifications to promote continued use.

In addition to notifications, information regarding the pregnancy is also deemed beneficial and a promoter of ongoing engagement. A study by Bush et al. (2019) notes that the most-used mobile application features were pregnancy and postpartum health milestone screening. However, a study by Musgrave et al. (2020) indicates that pregnant women deem fetal movement awareness, pregnancy weight and breastfeeding features as valuable behavioural change indicators.

Nonetheless, these features are strongly related to pregnant women in general. mHealth apps are developed to meet a targeted behavioural change; in the context of this study, the behavioural change required is consistent fetal dose recording. Given the availability of a vast array of pregnancy apps and the limited engagement of well-being features of *PregiDose*, it can be assumed that the *PregiDose* app can remain within the confines of fetal dose tracking and radiation education.

Lastly, the participants recommended automation. Automation is defined as computers or machines operating without the need for human intervention (Parasuraman & Mouloua, 2018). In the context of mHealth, the concept of the Internet of Things (IoTs) has grown rapidly in recent years. The IoT constitutes an interconnected network of hardware or software intended to provide automation in collecting health information (Kashani et al., 2021). Examples of the IoT in health include wireless body area networks (WBANs) and radio frequency identification (RFID) (Kashani et al., 2021). In the context of this study, the participants were still required to input data manually into the mobile application. Hence, the concept of automation could eliminate the prevalence of inconsistent mobile application usage, whereby readings are automatically captured without any human computation.

6. CONCLUSION

PregiDose is a mobile application developed for pregnant radiographers with the behavioural change target of enhancing fetal dosimetry, specifically concerning the consistent and accurate monitoring of fetal radiation doses. The study’s findings indicate positive views of the usefulness of the app, whereby the app offered a modern method of dose tracking in keeping with technological advancements in the context of self- tracking. This enables the pregnant radiographer to accurately keep track of her daily doses and thus ensure the safety of mother and the unborn child, who are exposed to ionizing radiation environments. Features to promote well-being were also included as supportive add-ons for pregnant radiographers, with the presumption of an all-in-one application. However given the availability of a vast array of pregnancy apps and the limited engagement of well-being features of *PregiDose*, it can be assumed that *PregiDose* can remain within the confines of fetal dose tracking and radiation education. The study revealed a need for automation, such as IoTs', within the occupational radiation safety context. This notion introduces several possibilities for future research to explore insofar as fetal radiation dose monitoring.

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Conflict of Interest

None

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5.2 Chapter 5 Conclusion

In this chapter, the mobile app *PregiDose* was used by pregnant radiographers in a real-life setting and evaluated for its usability and usefulness. The usage and evaluation were executed through a qualitative approach to explore and describe the users' perceptions regarding the app. From these results, the study concludes that the users found the app mostly usable, however there were a few technical challenges that could be improved on. The participants also found the app useful; however, they recommended that it would be more helpful if fetal dosimetry practice was automated. This is noted as a significant area for future research, upon which the next chapter elaborates.

CHAPTER 6: SYNTHESIS OF FINDINGS – DSR STEP FIVE

"*The end…is just the beginning*"

Bethany Hamilton

6.1 Introduction

In this chapter, the completed research cycle and its methods are synthesised under the research objectives outlined in Chapter 1. This chapter aims to provide the answer to the research questions posed at the onset of the study. These questions are answered by following the DSR theoretical framework used to guide the study. The research results were presented in Chapters 2 to 5. However, the overall research findings are discussed in this final chapter, followed by an evaluation of the study per the DSR criteria, confirming that the developed artefact meets all the requirements for a DSR artefact. The study's significance and contribution are evaluated, as well as the limitations encountered during the research. Lastly, the chapter describes recommendations for practice and future research and states the overall conclusion.

6.2 Reflection on the DSR Framework

Chapter 1 introduced the reader to the concept of design science research and its theoretical framework. This study followed the DSR steps to execute the research: 1) Problem awareness, 2) Suggestion, 3) Development, 4) Evaluation, and 5) Conclusion. Figure 2 was presented in Chapter 1, describing the components of each step in the DSR framework. Despite appearing similar to Figure 2, Figure 5 now presents the application of the DSR process in this study and further elaborates on the different methods used within each step, such as quantitative and qualitative. Vom Brocke et al.[124] support this and states that diverse research methods are applied in DSR research, including those well-rooted in the social sciences.

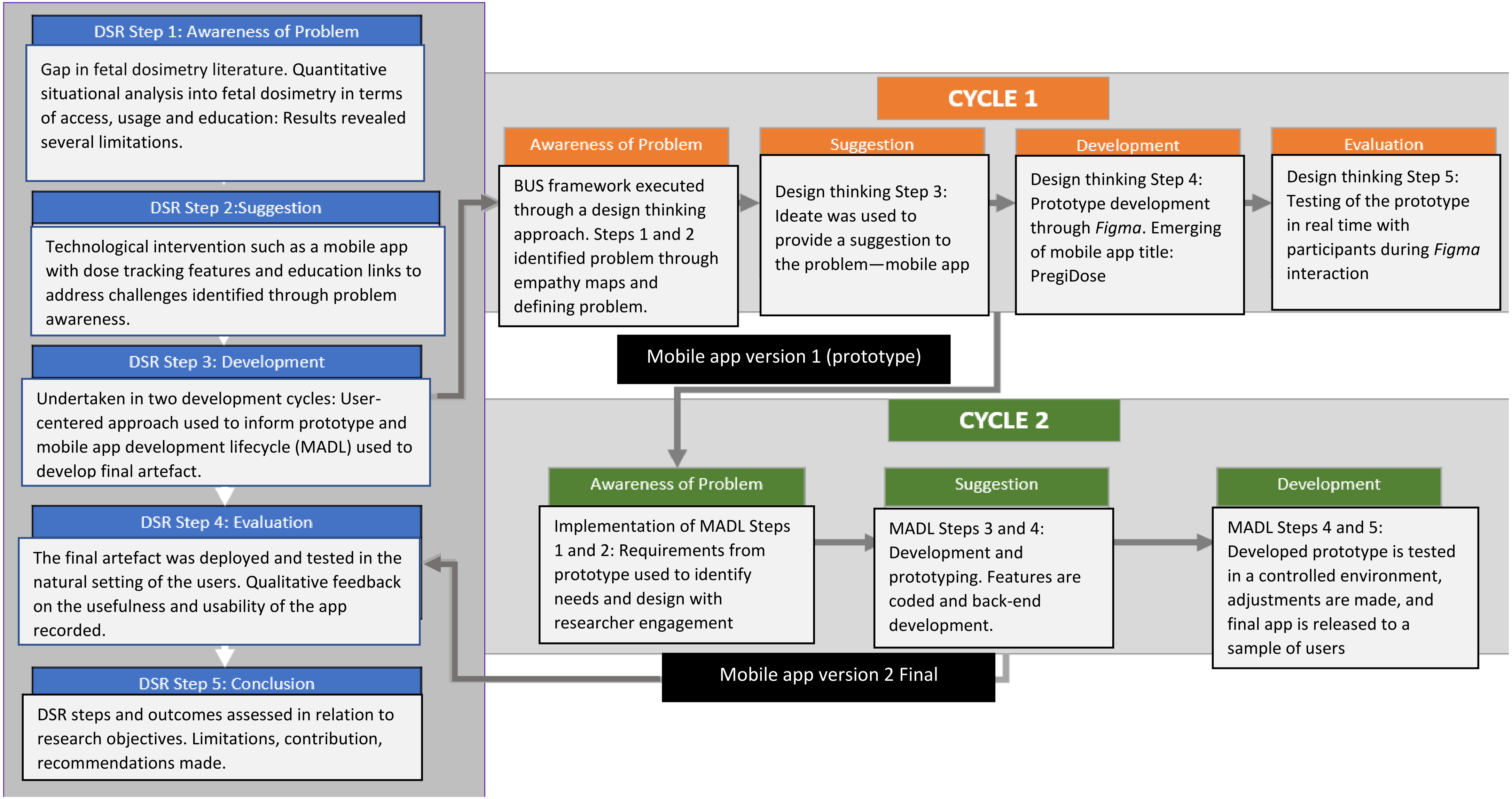

Figure 5: Application of DSR steps in the context of this study.

6.3 Answering the Research Question

At this juncture, the reader is reminded of the overarching research question of the study which is: How can a mobile application be developed to enhance the recording and monitoring of fetal radiation doses as well as provide education regarding the usage of dosimeters to pregnant radiographers? The sub- research questions (blue) were used to answer the main research questions. These questions are aligned with both the study objectives (white) and steps of DSR process.

Question 1. What methods are being used by pregnant radiographers to record and monitor the radiation doses to their fetus?

Objective 1: To understand the problem as it exists in the literature through problem awareness strategies.

Objective 2: To perform a situational analysis on fetal radiation dose monitoring methods and radiation safety education among female radiographers in the clinical enviroment.

In Question 1, the researcher sought to understand the problem in the literature and real life to identify an insufficiency that would support the use of a mobile application. Therefore, the results from Chapter 2 and Article 1 in Chapter 3 answer this question.

Question 2. What processes must be followed to develop the prototype mobile application?

Objective 3: To develop a prototype of the mobile application based on the situation.

In Question 2, the researcher investigated what processes were needed for the development of a prototype. The first version of the mobile application was the prototype, where the design and core features of the app were determined and often incorporated a user-centred approach. Hence, the results from Manuscript 4, Chapter 4 answer this question.

Question 3: What are the views of the mobile app end users regarding its useability and usefulness towards fetal dose monitoring, recording and education

Objective 4: To determine the useability of the mobile app for fetal dose monitoring, recording and education.

In Question 3, the researcher seeks to understand how the final mobile app can be assessed on its useability and usefulness. Useability refers to the technicalities of the app that enable it to function effectively for its intended purpose. In this study, this question is answered in Manuscript 4, Chapter 4 through a technical report, which elaborates on methods development and useability testing. The participants also reflected upon the useability of the app in Manuscript 5, Chapter 5. The researcher also sought to understand if this app was useful for its intended purpose, which is fetal dose recording, monitoring and education. This question was also answered in Manuscript 5, Chapter 5, whereby the usefulness of the app was evaluated through a qualitative approach.

Therefore, it is evident that all the research questions were answered in this study, which strongly aligned with the research objectives and DSR framework.

6.4 Discussion of Research Findings

The results from each step of the DSR process (Figure 5) were described in each chapter. The researcher now presents the overall findings and answers the research questions. In this study, four main findings emerged: 1) radiographer compliance with personal dosimetry, 2) challenges facing pregnant radiographers in South Africa, 3) *PregiDose* as an mHealth application to support occupational radiation health and safety, and 4) advancing *PregiDose*: The future of radiological protection reimagined.

6.4.1 Radiographer Compliance with Personal Dosimetry

In DSR Step 1, Problem Awareness, several results emerged from the literature. Here, the awareness emerged that many radiographers were non-compliant with personal dosimetry and did not often use their dosimeters. Some reasons for this were the fear of losing the expensive device, as well as attitudes and social norms, whereby low-risk radiation doses did not compel them to wear it, and forgetfulness.[26-27] After the situational analysis of pregnant radiographers, the study discovered that the challenges facing general and pregnant radiographers regarding dosimetry are concurrently similar and unique. The similarities include forgetfulness, which might be heightened in a pregnant woman; unique challenges for pregnant radiographers include the issue of limited access to fetal dosimeters and a lack of training on their usage.

6.4.2 Challenges Facing Pregnant Radiographers in South Africa

The situational analysis in DSR Step 1 revealed new knowledge on access, usage and education regarding fetal dosimetry among pregnant radiographers. The main area of concern was employers not facilitating access to dosimeters. In the context of radiology, dosimeters are considered an occupational health and safety measure that contributes to the mitigation of increased radiation dosages to fetuses.. Although a dosimeter is not a radiation protection device by itself, it can inform a pregnant radiographer in real time about increased radiation exposure in the working environment as a result of a leak or damage to lead shielding,[28] whereby a pregnant radiographer can remove herself immediately from that environment and be reallocated to safer working conditions.[7] Therefore, it is imperative that all pregnant radiographers can access these dosimeters, which should be provided by employers.

According to the Occupational Health and Safety Act 85 of South Africa,[29] employers have the following obligations towards their employees:

> a) "*Every employer shall provide and maintain, as far as is reasonably practicable, a working environment that is safe and without risk to the health of his employees".*

b) "Establish what precautionary measures should be taken with respect to such work, article, substance, plant or machinery in order to protect the health and safety of persons, and he shall provide the necessary means to apply such precautionary measures.

c) Providing such information, instructions, training and supervision as may be necessary to ensure, as far as is reasonably practicable, the health and safety at work of his employees.

Therefore, it is evident that the current and historic challenges presented in this study contravene the above-mentioned specific obligations. The empathy map of DSR Step 3 in this study highlighted that some pregnant radiographers felt unsafe, and their environments evoked fear in them (Manuscript 3). Precautionary measures to mitigate unnecessary exposure to the fetus include the use of a fetal dosimeter together with a general dosimeter. Employers, particularly in South Africa, should be familiar with the conditions related to the code of practice for users of medical X-ray equipment and the management of pregnant radiographers to be in a position to determine precautionary measures and ensure their provision.[30-31] Article 1, Chapter 3 highlighted that a lack of training with fetal dosimeters might be the cause of their under-utilisation. This is another example of the Occupational Health and Safety Act 85 not being adhered to by employers who had indeed issued dosimeters to pregnant radiographers. These challenges translate into pregnant radiographers being unable to record their fetal doses effectively to estimate the exposure to the fetus accurately, which is recommended by the ICRP.[32]

The discussion presented in Article 1 largely focused on the technical aspects of health and safety; however, pregnant radiographers also grappled with fears on a psychosocial level. In the empathy map of DSR Step 3 (Manuscript 3), pregnant and previously pregnant radiographers described the prejudice they experienced in the clinical setting about an inability to function fully in the workforce because they could only engage in limited activities, causing them to feel 'useless'. These factors contribute to poor emotional and mental well-being. Mental wellness in the workplace has become of great concern in recent years.[33] The effects of decreased mental wellness include reduced attention, fatigue, reduced performance and absenteeism.[34] However, for a pregnant radiographer subjected to the fast-paced environment of the radiology department and the anxiety associated with ionising radiation, these effects can be heightened. Hence, the findings in this article answers research sub question a) , which is, What methods are being used by pregnant radiographers to record and monitor the radiation doses to their fetus?

6.4.3 PregiDose as an mHealth Application to Support Occupational Radiation Health and Safety

In this discussion, two broad concepts are combined, namely mobile application in healthcare and occupational health and safety for radiation protection. In DSR Step 1, the study identified mHealth applications as technological advancements towards improving the monitoring and recording of health activities, as reported in the literature. The identified deficiency was that mobile applications in the context of radiography were limited. Therefore, the suggestion was a mobile application. In the development cycle 1, the full concept of *PregiDose* emerged. *PregiDose* was the first mHealth application dedicated to pregnant radiographers to support fetal dosimetry for all with access to a fetal dosimeter. *PregiDose* encompasses several features that directly support occupational radiation health and safety for a pregnant radiographer with a dosimeter. As described in Chapter 1, the ICRP recommends a threshold limit of 2 mSv throughout the pregnancy.[35] The app's core functionality is that of a dose tracker, whereby pregnant radiographers can insert their daily readings and view the accumulative doses. This would allow radiographers to take precautionary measures should doses be found exceeding threshold limits.[7] The share function of the dose-tracking feature enables the pregnant radiographer to save their dose record and share it with her employer or medical physicist for record-keeping. This not only assists the employee but also the employer, who is required to store dose records for up to 10 years.[30] The app also has an educational feature whereby pregnant radiographers can access links to policies and guidelines specifically developed for them, as well as links to access an expert, such as a medical physicist. These features were designed to provide information, support and training opportunities to pregnant radiographers should they be unsure how to use the dosimeter.

Therefore, it is evident that *PregiDose* addresses some of the requirements outlined by the ICRP, SAHPRA and the Health and Safety Act 85.

6.4.4 Advancing PregiDose: The Future of Radiological Protection Reimagined

Manuscript 5, Chapter 5, described the benefits of the *PregiDose* mobile application. However, the end users indicated that although the app was beneficial, it remained a manual process dependent on the user; hence, the participants recommended automation. The idea emerged that the concept of the Internet of Things (IoT) could potentially play a significant role in the future of occupational radiation safety. Rose et al.[36] define the IoT as follows:

> *The term Internet of Things generally refers to scenarios where network connectivity and computing capability extends to objects, sensors and everyday items not normally considered computers, allowing these devices to generate, exchange and consume data with minimal human intervention.*[36]

In the context of this study, objects and items can refer to pocket reading alarm dosimeters (PRAD). These dosimeters already generate radiation dose readings yet can also potentially automatically upload data to the mobile app without intervention from the pregnant radiographers.

This IoT was realised by Kim et al.,[131] who developed a radiation exposure monitoring system for underwater exposure. That device was connected to a mobile app to monitor radiation values generated from the detector.[37] However, Ishigaki et al.[53] utilised an actual mobile device to serve as the radiation detector for non-health workers living in Fukushima, where the Daiichi Nuclear Power plant accident occurred.[6] This led to several other developments in mobile app technology being used as radiation detectors. Johary et al.[132] describe how advanced image sensors in smartphone cameras can detect ionising radiation in addition to visible light. Although the measurements are reported not as accurate as a dosimeter, it is sufficiently useful to detect radiation levels before they reach threshold limits.[38] The limitations associated with this technology are that smartphones' heat and battery levels can influence the accuracy of the app. The authors further report that it is imperative to evaluate the image sensors of commercially available smartphones before they can be used as radiation alarms.[38]

Therefore, it is evident that dosimeters and smartphones can serve as IoT devices for radiation dose monitoring. However, their usefulness and usability have not been widely explored in the context of healthcare, particularly for pregnant radiographers. This technological innovation could potentially solve the challenges reported in Section 6.4.2 about access, as it is cheap, easy to operate and accessible. However, the point of concern with the adoption of such technology is regarding the sensitive nature of pregnant radiographers, whereby doses must be accurate for the safety of the fetus.

6.5 Evaluation of the Artefact Apropos the DSR criteria

As the study draws to an end, it is fitting to reflect on the criteria by Dresch et al.[39] for conducting studies with a DSR framework, namely 1) design as an artefact, 2) problem relevance, 3) design evaluation, 4) research contribution, 5) research rigour, 6) design as a research project, and 7) communication of the research. These criteria encompass the research processes described throughout this thesis and serve as validation that the study is indeed an application of the DSR framework. Table 9 reflects how the study's research outputs contribute to the Dresch et al.[133] criteria:

Table 9: Reflection on the DSR Criteria Used in this Study

Design as an artefact	The DSR method must produce an artefact: In this study, the artefact was the following: *PregiDose*, a mobile application to enhance fetal dose recording among pregnant radiographers	Manuscripts 3, 4 and 5
Problem relevance	The artefact was user-centred and guided by two aspects of the study: • Problem awareness: Inconsistent fetal dose recording methods, as described in Manuscript 1 of Chapter 3 • Design thinking: Steps 1 and 2 (empathy map and defining the need with insight). Accordingly, these two aspects ensured that the app addressed real-life problems pregnant radiographers experienced.	Manuscript 1 Manuscript 3
Design evaluation	The artefact must prove to be both useable and useful to the end user. The following methods were used to evaluate these two utilities: • Useability: Tested in a controlled environment under the management of the software engineers embedded in the MADL process as well as in the real life environment with pregnant radiographers. • Usefulness: Qualitative exploration after the participants engaged with the artefact in the real-life setting	Manuscript 4 Manuscript 5
Research contribution	The research contributed to both theoretical and empirical research, as well as societal impact in terms of SDGs and NDP goals.	Chapter 6 (Section 6.5)
Research rigour	The research study rigorously followed the DSR steps outlined in Chapter 1. The development of the artefact was guided by the following models: • Prototype design: BUS framework Design Thinking • Final artefact: Mobile app development lifecycle (MADL) • Trustworthiness of qualitative research findings—narrated verbatim (Appendix O) and thematic analysis.	Chapter 1 Manuscript 3 Manuscript 4 Appendix O
Design as a research project	An effective artefact requires the use of available means to achieve the desired purpose.[39] In this study, the available means was access to research funding from the National Research Foundation (NRF) and the Department of Higher Education, University Capacity Development Program (USDP). These funds were used to procure the services of software developers from industry to develop the artefact.	

Communication of the research	The research must be communicated to an audience well-versed in information technology as well as in management. Accordingly, the results were disseminated through publications and conferences to both scholars and stakeholders in radiography alike.	Chapter 6 (6.5.3)

Table 9 outlines the criteria described by Dresch et al.[39] and supported by Van der Merwe et al.[40] Therefore, it is evident that the study meets all the criteria of a valid DSR artefact.

6.6 Significance and Contribution

Research contribution is defined as the impact on and significant value of a research study to a particular field of study. In this study, the valuable contributions made can be categorised as theoretical, empirical and societal.

6.6.1 Theoretical and Empirical Contributions

The theoretical contribution includes synthesising existing knowledge, identifying gaps, and proposing novel insights or perspectives[41]. Empirical contributions involve generating new knowledge through data collection in real-world settings. Both contribute to broader scientific literature. Table 10 presents these contributions.

6.6.2 Societal Contribution

The societal contribution of research relates to successful research outputs that are used to uplift and benefit society[42] These contributions include products such as devices and services that are made available to society[42]. In In this study, the mobile application will be commercially available to all pregnant radiographers, both globally and locally. Transformative research contributes to the upliftment of society, whereby methodologies are carefully selected to include vulnerable populations and interventions that support the challenges uncovered through the research.[43] In this study, this was achieved by providing a "voice for the vulnerable", namely pregnant radiographers. The contribution provided awareness of the challenges that are faced, such that employers can strive to make positive changes within their departments.

Thus, research is not limited to scholarship but should also contribute to the UN's Sustainable Development Goals. Chapter 1 described the pertinent SDG goals being addressed in this study. These goals aim to improve and uplift societies, often through multidisciplinary approaches.[44] However, Rosen[136] encourages scholars not only to focus on the SDGs in isolation but rather to take a national approach towards tailoring the SDG objectives to each country's circumstances. In South Africa, the National Development Plan (NDP) 2030 aims to eliminate poverty and reduce inequality. Although this study does not directly address this aim, other objectives ultimately leading to this can be reflected upon. These include NDP 7, Positioning South Africa in the World; NDP 9, Improve Education; Training and Innovation; and NDP 10, Promoting Health. Theoretical and empirical contributions to this study align with the UN SDG and NDP goals described in Table 10.

6.6.3 Dissemination of Results

Disseminating results is an important aspect of the research contribution, as it is an active effort to exchange knowledge between the researcher and all stakeholders in the research[41]. Dissemination through conference presentations and proceedings thereof serves as a valuable tool for education and awareness of the research findings, presented in an easily understandable manner, which could potentially influence current practices. It further fostered research collaboration, whereby participants who had engaged in the study were not made to feel like subjects from which to gain data but rather like members of a collective effort to improve fetal dosimetry among all pregnant radiographers. In this study, the results were shared with local and international radiography communities alike at the conferences listed below:

Society of South African Radiographers (SORSA) Congress 2023 Cape Town

Oral presentation: *Voice of the vulnerable: A situational analysis into fetal dosimetry among pregnant radiographers in South Africa*

DSR Step 2 results from situational analysis. The stakeholders of this conference included radiographers, managers and medical physicists from across South Africa. It was an integral part of the research process to share findings with the local radiography community, as this is the context within which the research problem exists.

ICRP 7th International Symposium on the System of Radiological Protection 2023, Japan

Oral presentation: *Pregi-dose: A mobile application to enhance fetal dosimetry among pregnant radiographers in South Africa*

University of Pretoria: Transdisciplinary Research Workshop 2024

Oral presentation*: Partnering for the goals: PregiDose a mobile app for pregnant radiographers.*

The audience at this workshop included scholars from all disciplines, including the humanities, engineering and health sciences. This was an opportunity to present the transdisciplinary aspect of the research and share practices that facilitated this collaboration. The stakeholders in this international conference included board members of the ICRP Executive Committee, radiographers, radiologists, medical physicists, quality assurance officers, and federal officers of radiation protection from across the world. The conference presented an opportunity to present my findings at this prestigious platform, whereby receiving the award for Best Scientist and Professional validates the work presented in this thesis. Furthermore, it enabled the researcher to contribute to the *Annals of the ICRP*. Articles from this journal are highly cited and serve as reference documents for guiding radiation protection practices worldwide.

Table 10:Theoretical and Empirical Contribution in Alignment with the UN SDGs and the South African NDP

Type of contribution		Details of contribution	Alignment with SDGs
Theoretical	Literature	• Literature on pregnant radiographers' compliance with fetal dosimetry in comparison to general radiographers • New knowledge on challenges facing pregnant radiographers regarding access and training on fetal dosimeters • New knowledge on defined needs that pregnant radiographers have.	SDG 3: Good health and well-being concerning pregnant radiographers in the workplace
Empirical	Frameworks, models and awards	• DSR framework for the development of *PregiDose* • Technical report on the mobile application development model (MADL) used to create *PregiDose* • Conference proceeding (Manuscript 2) international award by the ICRP gaining international recognition https://www.icrp.org/page.asp?id=411	SDG 9: Industry, Innovation and Infrastructure Application of existing methods to the development of an innovative artefact in collaboration with industry NDP 7: Positioning SA in the world
	Artefact	• *PregiDose*: a fetal dose tracking mobile app for pregnant radiographers	SDG 17: Partnership for the goals Transdisciplinary collaboration towards the realisation of the artefact NDP 9: Improving education, training and innovation.
	Radiation protection	• Occupational health and safety facilitated through mobile app technology	SDG 3: NDP 10: Promoting health
	Transdisciplinary	• Transdisciplinary collaboration between radiography and informatics towards health informatics and mHealth.	SDGs 9 and 17

6.7 Limitations

The researcher is happy to report that all processes planned in this study went well. Only two things can be reports as limitations of this study.

The first limitation relates to data collection and sample sizes. In Phase 4, the app was tested in a real-life setting, and its usefulness was assessed through qualitative interviews. Seventeen pregnant women engaged with the app, although only four pregnant women responded to the invitation. The invitation was followed up with several phone calls and messages; however, there was still no response. Therefore, the researcher reflects on a participant's right to autonomy, whereby she was at liberty to engage with the app but was not compelled to participate in an interview, as described in Manuscript 5. Whilst small sample sizes can be justified in qualitative research, the inclusion of more pregnant woman with access to fetal dosimeters would have beneficial. Another contributor towards the small sample size could also be related to time. A longer time frame (more than five months) for data collection may have yielded more participants.

The second limitation also relates to sample size, namely the number of pregnant radiographers in South Africa. The workforce of South African radiographers comprises a heterogeneous group from males and females of child-bearing age to radiographers close to retirement. This reduced the pool of pregnant radiographers which was evident in the quantitative survey of DSR 1, problem awareness through situational analysis.

6.8 Recommendations

This study makes the following recommendations related to clinical practice for pregnant radiographers, future research and sustainability with regards to addressing the limitations and exploring the advancement of *PregiDose*.

6.8.1 Recommendations for Practice

The study identified pregnant radiographers' access to dosimeters as the largest contributing factor to non-compliance and further, employers failing to provide dosimeters. Dosimeters are occupational health and safety devices for radiation workers and are prescribed by SAHPRA as a requirement for licence holders of X-ray equipment. Therefore, the study recommends implementing a top-down approach whereby the availability of dosimeters is checked when radiation board assessments are made. Penalties should be issued to departments that do not provide support to their pregnant radiographers. The study further recommends reporting such instances to SAHPRA without the risk of punitive measures from the employer or the risk of job losses. The study also recommends that radiography departments in South Africa adopt a structured approach towards pregnant radiographers, as described in Chapter 2, whereby such radiographers receive education and training on their personal dosimeters, which is another challenge pregnant radiographers experience. Lastly, this study advises employers and colleagues to be aware of the physical and emotional changes pregnant women experience while working in the department. This awareness is essential for offering supportive assistance to pregnant radiographers, who play a pivotal role in creating future generations.

6.8.2 Recommendations for Future Research

In keeping with *PregiDose* as a mobile app, this study recommends a longer timeframe for recruitment and engagement to increase the sample size. Section 6.4.4 contains the formulation of the idea of advancing *PregiDose* through the concept of automation. This was supported by existing research in other contexts, which connected dosimeters to mobile apps or used the mobile device itself as a radiation monitor. Within the scope of this study, the utilisation of these established technologies and new ones, such as smart watches, could be investigated. However, this exploration would necessitate the collaboration of a diverse team comprising engineers, software developers, and medical physicists.

6.8.3 Sustainability of the developed application

The mobile application was made available to the users for the period of usefulness testing in the real-life setting. After the data analysis presented in manuscript 5, the mobile app server was discontinued. Prior to any conference attendance and publication, the researchers and software engineers approached the University of Pretoria department of Research and innovation, commercialisation unit. An invention disclosure form was completed and the percentage distribution of the creative contribution was established. The title PregiDose, and logo were then copyrighted. The app itself could not be patented as mobile applications are open to any software developer to use.

The researcher intends to sustain the app after the thesis submission by commencing with the advancement process initiated through the commercialisation unit. The role of this unit is to facilitate the successful transfer of innovative research and intellectual property from the academic setting to the commercial sector. The app will either be subcontracted to a company and run under the university commercialisation unit, or the intellectual property will be sold outright to a capable vendor who is able to advance and support the app on a long-term basis. Elaborate recommendations from this study will be made available to software developers advancing the app. These include the inclusion of both IoS and android hosting, the usability issues and recommendations noted by the users in manuscript 5 as well as the need for future updates. The financial aspect of the app being free or a third-stream income for the university will be further discussed with the commercialisation unit.

Once the commercialization pathway has been established, a mobile app privacy policy will be drawn up which will comply with data protection regulations such as the PoPi act. The user will be required to consent to the privacy policy prior to installation. This is to protect sensitive data from the pregnant radiographers.

6.9 Conclusion

The United Nations SDG goal number 17, Partnering for the Goals, aims for societies to form partnerships towards the common goal of uplifting society. In this study, the result of this transdisciplinary collaboration facilitated translational research that can be equated to the phrase, Partnering for *PregiDose.* The phrase is multifaceted, harnessing all the steps of DSR towards a common goal. The research exemplifies transformative research through transdisciplinary partnership, whereby real-world problems facing pregnant radiographers were solved using methodologies deeply rooted in informatics. Lastly, the research findings give rise to several technology-driven research ideas, which reimagine the future of radiological protection. Therefore, this research ends with a new beginning for the radiography profession.

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Appendix A: Proof of Article 1

Journal of Radiology Nursing 42 (2023) 496–503

Contents lists available at ScienceDirect

Journal of Radiology Nursing

journal homepage: www.sciencedirect.com/journal/journal-of-radiology-nursing

Fetal Dosimeter Access, Usage, and Training Among Pregnant Radiographers in South Africa

Hafsa Essop, MRad, BRad Hon [a,*], Mable Kekana, PhD, MTech [a], Hanlie Smuts, PhD, MSc [b], Andries Masenge, MSc [c]

[a] *Faculty of Healthcare Sciences, Department of Radiography, University of Pretoria, Pretoria, South Africa*
[b] *Faculty of Engineering, Built Environment and Information Technology, Department of Informatics, University of Pretoria, Pretoria, South Africa*
[c] *Faculty of Agriculture and Natural Sciences, Department of Statistics, University of Pretoria, Pretoria, South Africa*

Keywords:
Pregnant radiographer
Occupational radiation safety
Fetal dosimeter
Radiation exposure
Compliance

A B S T R A C T

Background: Pregnant radiographers require more stringent occupational safety monitoring through fetal dosimetry because of the sensitivity of their fetuses' cells to radiation. This study aims to describe fetal dosimetry among pregnant radiographers as regards access, usage, and training.
Methods: Quantitative data were collected using an electronic national survey. The study collected 89 responses from pregnant and previously pregnant radiographers in South Africa between January 2021 and April 2021.
Findings: The responses revealed that 53.9% (n = 48) of participants had never been issued with a fetal dosimeter. This situation was mostly attributed to the employer and financial constraints (n = 29). Of those with access to fetal dosimeters, 46.1% (n = 41), only 56% (n = 28) indicated that they always wore it. An alarming 52% (n = 26) never consistently recorded fetal doses.
Discussion: Most pregnant South African radiographers do not have access to fetal dosimeters. Many of them remain noncompliant, which might be attributed to a lack of training and knowledge about the device.

Introduction

Radiation workers practice in potentially hazardous environments within radiology departments as a result of ionizing radiation used for diagnostic medical imaging (Sherer et al., 2017). Pregnant radiographers are considered high-risk individuals due to the increased sensitivity of the fetus's developing cells (International Atomic Energy Agency, 2022). Exposure to radiation has the potential to cause genetic effects and cancer within the fetus, depending on the amount of radiation dose received. A primary method of ensuring that occupational radiation doses remain within regulatory limits is through occupational radiation dose monitoring (American Association of Physicists in Medicine, 2019). This is achieved through personal dosimeters, also known as fetal dosimeters, which are worn by pregnant radiographers and provide real-time radiation dose measurements. A situational analysis done to investigate compliance of fetal dosimeters revealed that many pregnant radiographers, particularly in South Africa, lack support with regard to the training on the use of the dosimeter as well as consistent record-keeping of the fetal dose measurement. This barrier renders the device as ineffective and hazardous to both mother and the unborn child. Mobile applications offer a wide range of benefits and are often inculcated within an individual's life to ensure effective monitoring of any health needs.

Introduction

Radiation workers practice in radiology departments where they may be exposed to ionizing radiation used for diagnostic medical imaging (Sherer et al., 2017). Due to the increased sensitivity of a fetus's developing cells to radiation, pregnant radiographers are a category of radiation workers whom the International Committee on Radiation Protection (ICRP) (International Committee of Radiation Protection, 2000) and the International

Conflict of interest: The author(s) have no relevant disclosures. There was no grant funding or financial support for this manuscript.
Funding: This work is based on the research supported in part by the National Research Foundation of South Africa (BAAP2204143433) and the University Capacity Development Program (UCDP) grant of the Department of Higher Education.
* Corresponding author: Hafsa Essop, Department of Radiography, University of Pretoria, 30 Bophelo Road, Gezina, Pretoria, Gauteng, 0186 South Africa.
E-mail address: Hafsa.essop@up.ac.za (H. Essop).

https://doi.org/10.1016/j.jradnu.2023.07.005
1546-0843/

Appendix B: Proof of Submission (Manuscript 2)

[Request] Submission of the Proceeding paper of ICRP 2023 Symposium External Inbox ×

Hyungjoon Yu hyungjoon.yu@icrp.org via icrp.onmicrosoft.com Thu, 23 Nov 2023, 10:16
to

Dear All live speakers,

Thank you for your participation and presentation at the ICRP 2023 symposium held in Tokyo.

Your presentation is set to be included in the Proceedings of the ICRP 2023 Symposium.
Kindly submit a concise paper, about 2-5 pages, related to your symposium presentation to Hyungjoon Yu, Assistant Scientific Secretary of ICRP, via email at hyungjoon.yu@icrp.org by **31st December 2023.**

Please note that your paper will undergo peer review after the submission and it is strongly recommended to adhere to the format provided in the attached template.

Thank you very much again and best wishes,

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Appendix C: Proof of Submission and Review (Manuscript 3)

Health Informatics Journal - Manuscript ID HIJ-23-0271 External Inbox ×

Health Informatics Journal <onbehalfof@manuscriptcentral.com> Fri, 6 Oct 2023, 00:09
to Hafsa.essop, Mable.kekana, Hanlie.smuts

05-Oct-2023

Dear Mrs. Essop:

Your manuscript entitled "Co-Designing of a prototype mobile application for fetal radiation dose monitoring among pregnant radiographers using a Design Thinking approach" has been successfully submitted and is presently being given full consideration for publication in Health Informatics Journal.

You can view the status of your manuscript at any time by logging in to sage.atyponrex.com/journal/jhi and clicking My Submissions. Sort by journal and submission status to locate this manuscript.

Your manuscript ID is HIJ-23-0271. Please mention this manuscript ID in all future correspondence.

Authors are strongly advised to ensure that the author by-line, the Corresponding Author, and the order of authors is correct at Original Submission. Only when an author has contributed to a study following feedback raised during peer review, will an author addition to the by-line be permitted. Changes to the author by-line by adding or deleting authors are NOT permitted following

Health Informatics Journal
Research Article

Co-Designing of a prototype mobile application for fetal radiation dose monitoring among pregnant radiographers using a Design Thinking approach

Submission Status	Under Review
Manuscript ID	HIJ-23-0271
Submitted On	7 October 2023 by Hafsa Essop
Submission Started	2 October 2023 by Hafsa Essop

This submission is under consideration and cannot be edited. Further information will be emailed to you by the journal editorial office.

Submission overview →

Appendix D: Proof of Submission and Review (Manuscript 4)

Preprint DOI Available External Inbox ×

JMIR Publications <no-reply@jmir.org> 21 Mar 2024, 07:06 (4 days ago)
to me, Mable, Jacques, Hanlie, Gunther

Thanks for your submission to JMIR / JMIR Preprints.

As requested through the preprint settings when you submitted the manuscript, your Preprint
"Implementation of a mobile application development model toward PregiDose: A fetal dose-tracking app for pregnant radiographers."
by Hafsa Essop, Mable Kekana, Jacques Brosens, Hanlie Smuts, Hanlie Smuts

is now available at http://preprints.jmir.org/preprint/58608 and has has been assigned the following DOI: 10.2196/preprints.58608.
It has been submitted to CrossRef and is also available through the DOI handle at http://doi.org/10.2196/preprints.58608 (this DOI handle will redirect to the URL above).

Please use the DOI to cite the submitted version in any grant proposal or for similar purposes (it will be updated with a link to the version of record once published), and feel free to tweet about it!

Please that the preprint is published now and we are not be able to "unpublish" it, as a preprint is supposed to be a stable and citable document.

Our FAQ for preprints is at https://jmir.zendesk.com/hc/en-us/articles/115001350367-What-are-JMIR-Preprints-

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Questions? Check out our knowledge base at https://support.jmir.org/hc/en-us !

Appendix E: Proof of submission (Manuscript 5)

IJMEDI-D-24-01056 - Confirming your submission to International Journal of Medical Informatics External Inbox ×

International Journal of Medical Informatics <em@editorialmanager.c... Tue, 14 May, 15:25 (4 days ago)

to me

This is an automated message.

Perceptions of pregnant radiographers regarding the usefulness and usability of PregiDose. A mobile application to enhance fetal dosimetry and well-being.

Dear Ms Essop,

We have received the above referenced manuscript you submitted to International Journal of Medical Informatics. It has been assigned the following manuscript number: **IJMEDI-D-24-01056**.

To track the status of your manuscript, please log in as an author at https://www.editorialmanager.com/ijmedi/, and navigate to the "Submissions Being Processed" folder.

Thank you for submitting your work to this journal.

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Appendix F: Ethics Approval Certificate

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Faculty of Health Sciences

Institution: The Research Ethics Committee, Faculty Health Sciences, University of Pretoria complies with ICH-GCP guidelines and has US Federal wide Assurance.
- FWA 00002567, Approved dd 18 March 2022 and Expires 18 March 2027.
- IORG #: IORG0001762 OMB No. 0990-0279 Approved for use through February 28, 2025 and Expires: 07/20/2028.

Faculty of Health Sciences **Research Ethics Committee**

15 February 2024

Approval Certificate
Annual Renewal

Dear Mrs H Essop,

Ethics Reference No.: 635/2021 – Line 1
Title: The development of a mobile application to enhance fetal radiation dose monitoring among pregnant radiographers

The **Annual Renewal** as supported by documents received between 2024-02-01 and 2024-02-14 for your research, was approved by the Faculty of Health Sciences Research Ethics Committee on 2024-02-14 as resolved by its quorate meeting.

Please note the following about your ethics approval:
- Renewal of ethics approval is valid for 1 year, subsequent annual renewal will become due on 2025-02-15.
- The Research Ethics Committee (REC) must monitor your research continuously. To this end, you must submit as may be applicable for your kind of research:
  a) annual reports;
  b) reports requested *ad hoc* by the REC;
  c) all visitation and audit reports by a regulatory body (e.g. the HPCSA, FDA, SAHPRA) within 10 days of receiving one;
  d) all routine monitoring reports compiled by the Clinical Research Associate or Site Manager within 10 days of receiving one.
- The REC may select your research study for an audit or a site visitation by the REC.
- The REC may require that you make amendments and take corrective actions.
- The REC may suspend or withdraw approval.
- Please remember to use your protocol number (635/2021) on any documents or correspondence with the Research Ethics Committee regarding your research.

Ethics approval is subject to the following:
- The ethics approval is conditional on the research being conducted as stipulated by the details of all documents submitted to the Committee. In the event that a further need arises to change who the investigators are, the methods or any other aspect, such changes must be submitted as an Amendment for approval by the Committee.

We wish you the best with your research.

Yours sincerely

On behalf of the FHS REC, Dr R Sommers
MBChB, MMed (Int), MPharmMed, PhD
***Deputy Chairperson** of the Faculty of Health Sciences Research Ethics Committee, University of Pretoria*

The Faculty of Health Sciences Research Ethics Committee complies with the SA National Act 61 of 2003 as it pertains to health research and the United States Code of Federal Regulations Title 45 and 46. This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki, the South African Medical Research Council Guidelines as well as the Guidelines for Ethical Research: Principles Structures and Processes, Second Edition 2015 (Department of Health).

Research Ethics Committee
Room 4-60, Level 4, Tswelopele Building
University of Pretoria, Private Bag X323
Gezina 0031, South Africa
Tel +27 (0)12 356 3084
Email: deepeka.behari@up.ac.za
www.up.ac.za

Fakulteit Gesondheidswetenskappe
Lefapha la Disaense tša Maphelo

Appendix G: Participant Information Leaflet and Informed Consent for Anonymised Questionnaire in DSR Step 1 (Problem awareness through Situational Analysis)

https://forms.gle/F7brXKezuce1mPeq8

Faculty of Health Sciences

Fakulteit Gesondheidswetenskappe

Lefapha la Disaense tša Maphelo

Development of a mobile application to enhance fetal dose monitoring among pregnant radiographers.

Researcher name: Mrs H. Essop (26036267)
Supervisors' names: Dr M Kekana, Prof H Smuts
Faculty of Health Sciences, Research Ethics committee (610/2021)

Title: The development of a mobile application to enhance fetal dose monitoring among pregnant radiographers.

I am a postgraduate student at the Faculty of Health care Sciences, Department of Radiography, University of Pretoria. You are invited to participate in phase 2 of this doctoral degree research, (Phase 1 completed in proposal phase) . The purpose of this phase, is to determine the current monitoring and recording methods used by radiographers who have been pregnant or are pregnant to ascertain aspects that need to be addressed. Secondly, to gain input from all female radiographers on the features that would be valuable to have in a mobile application to monitor fetal doses among pregnant radiographers. This will inform the design of the mobile application. You may contact the researcher on 0715897939/ hafsa.essop@up.ac.za, should any question need further clarity.

Note: The implication of submitting the questionnaire is that informed consent has been given by you. Thus any information derived from your form (which will be totally anonymous) may be used for e.g. publication, by the researchers. If you have provided your information to be contacted in phase 4, your information will still remain confidential and will not in any way be published or distributed.

We sincerely appreciate your valuable input .

Kindly indicate if you are prepared to share anonymous experiences and views regarding dose monitoring and recording in pregnancy *

- Yes
- No

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Appendix H: Invitation to Participatory Design Thinking Workshop for DSR Step 3: Development of Mobile App Prototype Design.

Good day

I hope this email finds you well

I am currently a researcher at the University of Pretoria. I am in Phase 3 of my doctoral study, which entails developing a mobile application for pregnant radiographers to enhance fetal dose monitoring. The first cycle of the development is a user-centred approach that requires input from individuals who are pregnant radiographers, previously pregnant or have experience with interacting with pregnant radiographers in terms of management and radiation safety.

You have been identified as someone who could offer a valuable contribution to this workshop which is aimed at informing the design of the mobile app prototype.

Attached, the ethics clearance certificate of the study and research proposal to offer you background into the study.

If you are willing to participate, kindly complete the following link as a form of implied consent to your participation in the workshop.

https://forms.gle/X5SgFnbUqp5CNxw56

I look forward to hearing from you

Kind regards

Mrs H Essop
12th December 2022

Appendix I: Program for Participatory Design Workshop (DSR 3 -Cycle 1)

Time	*Activity*	*Facilitator*
08h00-08h15	Tea	
08h15-08h30	Welcome & briefing about the Design thinking process	Dr Weilbach
08h30-08h45	Participant introduction	All participants
08h45- 10h15	Step 1: Empathize	
10h15-10h30	Tea break	
10h30-11h30	Step 2: Define	Dr Weilbach
11h30-12h30	Step 3: Ideate	
12h30-13h15	Lunch	
13h15-14h30	Step 4: Protype wireframing (Figma – interface design)	Mr Strydom
14h30-15h30	Step 5: Evaluate	Mr Strydom
15h30	Conclusion and vote of thanks	Mrs Essop

-End-

Appendix J: Participant Information Leaflet and Consent for Engagement with Mobile App and Individual Interviews in DSR Step 4.

https://forms.gle/Ak8q2TndEBUqKkQa6

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Faculty of
Health Sciences

Fakulteit Gesondheidswetenskappe
Lefapha la Disaense tša Maphelo

Invite to engage with PregiDose: A mobile application for pregnant radiographers

This invite is extended to all pregnant radiographers in South Africa who would like to engage with the mobile application for at least one month of their pregnancy, as part of Phase four of a doctoral research study. If you are interested, kindly provide complete with your contact details and I will contact you with further information and documentation. Completion of this form serves as a consent to engaging with the mobile application and providing feedback thereof. You participation in completely voluntary. You are at liberty to withdraw from this study at any given time and you may decide if you want to be interviewed or not. Your details will remain completely anonymous and only the researcher and development team will have access to your dose records to ensure that the app is functioning efficiently.

Mrs Hafsa Essop: Principle researcher

Appendix K: Guidelines for the Use of PregiDose

Faculty of Health Sciences
Fakulteit Gesondheidswetenskappe
Lefapha la Disaense tša Maphelo

GUIDELINES FOR USING PREGI-DOSE: A MOBILE APPLICATION TO ENHANCE FETAL DOSE MONITORING AND WELLNESS AMONG PREGNANT RADIOGRAPHERS

Congratulations on your pregnancy!

We would like to thank you for your interest in participating in this study. PregiDose is a mobile application that was specifically designed for pregnant radiographers by a panel of users and experts. The mobile application is not a dosimeter, but rather a dose tracking platform, that replaces manual methods of recording, such as a logbook. It also has additional features specifically designed to support you as a pregnant radiographer.

1. Installing the PregiDose APK file.

Before installing the file, kindly click on the following link and follow the step-by-step guidelines on how to remove firewalls that may inhibit you from downloading and installing the app.

https://www.groovypost.com/howto/install-apk-files-on-android/

2. Using PregiDose

Upon consenting to your participation, you will provide the researcher with your demographic details, in order to register you onto the temporary host. You will then be required to do the following tasks:

Getting started

- Ensure you know how to operate your fetal dosimeter
- Set your daily threshold limit of 0.02mSv
- Set your threshold alarm
- Set dose unit to Millisieverts
- Able to get your daily dose reading to be able to input in the mobile application
- Ensure you know where to place the dosimeter correctly on your body

*The mobile application has a contact an expert feature. if you have challenges regarding any of the above you are welcome to contact Ms Molatedi (Medical Physicist) for assistance.

3. Daily recordings

- On the app, set an alarm time that suits you to input your daily reading. This time should ideally be consistent.
- Open the record dose link and input your reading.
- Should you miss a dose reading in the event of being absent from work or working night shift, please indicate the reason in response to the missed dose.
- You will be required to engage with the app for only one month, so we can determine if it was useful or not.

4. Mobile Application Education and Wellness Features

You are encouraged to engage with both features in order to provide constructive feedback during the post-participation interview.

4.1 Education features

This section includes international and South African policies regarding pregnant radiographers. It also includes limited information of the use of the dosimeter and instructional videos thereof.

4.2 Wellness features

The self-care feature includes links to pregnancy exercises as radiographers are encouraged to maintain fitness due to the physical demands of their daily work.

A journalling feature is also included, whereby you can document your thoughts, feelings and experiences regarding anything relating to your pregnancy, the mobile application and working environment on a weekly basis. Engaging in this feature is completely optional, however, encouraged. Information presented can be used towards improving the mobile application, in the event that you may forget to report on an important experience during the interview.

A social feature is also enabled, whereby you will have access to a WhatsApp link to join a pregnant radiographer group. This is completely optional if you would like to connect with other pregnant radiographers.

5. Feedback

The most valuable part of this phase of the study is to attain your feedback. After one month of engaging with the mobile application, I will then conduct an online interview with you regarding all features of the mobile application. This feedback session is critical to determine if the app is useful for pregnant radiographers and what can be done to improve it.

6. Confidentially and Privacy

The data from this phase of the study will include the following:

- Your dose reading reports for the month,
- Journal entries
- The number of times a section was engaged
- Post-participation interview recording

Only the researcher and the selected members of the developing team will have access to your doses. You will be registered using a code name. This will ensure that your data is anonymised to the team of mobile application specialists who will be analysing your data from the mobile application. During the post participation engagement interview, you will continue to use your code name, therefore all your information will remain anonymised.

7. Medico-legal

This mobile application is still in a trial phase. You are therefore required to indicate your original method of fetal dose recording (example note book/ service provider software) and continue with it whilst engaging with the mobile application. This is an important safety requirement of the study, as unforeseen technical problems may arise with the mobile app, of which you could lose your valuable data.

I trust this document has been able to answer most of your questions. If you are satisfied with the information provided and are willing to participate, kindly complete the consent form document.

If you have any further queries please do not hesitate to contact me

Mrs Hafsa Essop – 0715897939 hafsa.essop@up.ac.za

Appendix L: Invitation to participate in an interview following engagement with the mobile application (DSR Step 4)

Good day #####

Thank you for engaging with PregiDose and including it in your pregnancy journey.

I have noted that you have engaged with the mobile application for a period of one month. I would therefore like to take this opportunity to invite you to a feedback session in the form of an interview, regarding your experience and views of PregiDose.

The interview can be telephonic and I will contact during a time that is most convenient for you.

If you agree to partake in this interview, kindly inform me of date and time for me to set up the interview.

The interview will be completely anonymous; however, it will be audio-recorded such that your direct words can be captured and relayed correctly.

I look forward to hearing from you and the experience that you have had with the app.

Kind regards

Mrs H Essop

Appendix M: Anonymised Database of Study Population (DSR Step 4)

Table 11:Database of pregnant woman who completed invite, downloaded app and participated in interview.

Participant code	Due date	Department	Downloaded app and registered	Access to dosimeter	Response to telephonic interview
1	11/11/2023	Diagnostic	No – Gave birth before downloading	-	-
2	29/03/2024	Diagnostic	Yes	No	No
3	05/10/2023	Diagnostic	No – Gave birth before downloading	-	-
4	13/02/2024	Diagnostic	No – No response to follow up	-	-
5	06/11/2023	Diagnostic	No – No response to follow up	-	-
6	04/03/2024	Diagnostic	Yes	No	No
7	12/04/2024	Diagnostic	No – No response to follow up	-	-
8	05/06/2024	Diagnostic	No – IoS phone use	-	-
9	26/01/2024	Diagnostic	Yes	Yes	Yes
10	15/02/2024	Diagnostic	Yes	Yes	No
11	13/06/2024	Diagnostic	Yes	No	Yes
12	06/03/2024	Diagnostic	No –IoS phone use	Yes	-
13	22/08/2024	Diagnostic	Yes	No	No
14	28/04/2024	Radiation therapy	Yes	Yes	Yes
15	23/04/2024	Diagnostic	Yes	Yes	No
16	25/10/2024	Diagnostic	Yes	Yes	Yes
17	-	Radiation therapy	No – IoS phone user	Yes	-

Appendix N: Semi-Structured Interview Guide Used (DSR Step 4).

Section A: Background

1. Did you have access to a fetal dosimeter?
2. When are you due?
3. Which department do you work in?

Section B: Experiences using PregiDose

1. What are your views on the usefulness of PregiDose during your pregnancy?
2. How did you experience the dose tracking feature?
3. What are your views on the education links?
4. What are your views on the wellness features, namely mindfulness and journaling?
5. What recommendations do you have to improve PregiDose?

Appendix O: Excerpt of Raw Data from Interviews (DSR Step 4)

INTERVIEW 1

Interviewer: All right, great, so let's start., you did give me all your details, but I just wanted to know, did you use a dosimeter? I think you said you didn't.
P1: No, I still haven't gotten a proper dosimeter. It's okay. So what method do you use or will you intend using to track your doses?
So I was told that they will be watching my normal dosimeter. Mm-hmm. Okay.

0:30

Interviewer: All right. So is it a TLD?, all right, no problem. All right, so I just want to talk about the app. Thank you so much for downloading it and engaging with it How was it to download? Was it how did you find the downloading of it?

P1: Wasn't so difficult. It was actually quite simple.

Interviewer: Okay, perfect. Okay. And then, so can you tell me anything, let's just be free for now before I ask you anything, but can you tell me anything, your feelings or your thoughts about the app?
P1: I think it's a very useful app. It's obviously if you have proper dosimeter. Yes.

1:18

P1: It's very useful and it does provide quite good information.
Interviewer: Okay. All right. So if you had to use a dosimeter, do you think it would be, you know, like feasible every day from your dosimeter you put in the doses like that?
P1: I think so.

1:54

P1: get a reading once a month from your TLD and then you can put it in the app? I think I can do that. I just ask them for the reading because they don't actually give the reading to us. They only report to us if it's too high.
Interviewer: Okay. And then how do you feel about that? Would you like the reading or would you not like it?
P1: Personally, I would like to.
Interviewer: All right. And then having said that, so you know there were different features of the app, and then the one was education links. Did you check on them, the guidelines?

2:38

P1: Yes, I did. Interviewer: All right. And what did you think about them?

2:42

P1: I think it was very nice. The South African guidelines are not very... Mm-hmm.

2:52

P1: But with the other guidelines, it's very... Mm-hmm. Okay, all right.

2:58

P1: So, like, the ICRP and the IAEA, they're more user-friendly, like, they're easy to understand.

Interviewer: Okay and then tell me there was also the things for other links for pregnant radiographers like well pregnant women like mindfulness and in that. Did you have a look at that?
P1: I did. I think it's very nice to have some information about other stuff that you can do.

3:47

Interviewer: Okay. And is there anything like that that wasn't there for a pregnant radiographer, a pregnant woman? Do you think that would be helpful to add it in the future?

P1: I think something that a lot of people would like to engage with is maybe some weekly information about your baby.

Interviewer: Oh, okay. Alright. So like the milestones and things like that. Okay, alright. It's always nice to see at this week they are a pumpkin seed and then next week they are a, at the end you're a watermelon or something like that.

P1: Exactly.

Interviewer: Okay, I also liked to follow that kind of thing when I was pregnant. Okay, great.

4:32

Interviewer: And then did you see that there was the social media links, like join a WhatsApp group and that kind of thing. Would you have liked to engage with other pregnant women, the social part?

P1: Would be nice. I didn't see the links.

Interviewer: Okay, no problem. Okay, alright. Is there any reason why you would want to connect with other pregnant radiographers particularly?

5:02

P1: It would be nice to find out if other people share the same struggles that you do. Yes, definitely. Okay. Alright. Okay, all right. And then lastly, did you see that there was a look for an expert or find it or speak to an expert?

P1: I didn't see that.

Interviewer: Okay, so it's there. But how important do you think it is to have that feature whereby there's an expert, there's a medical physicist, there's somebody who knows a lot about pregnancy and radiation.

5:33

Interviewer: Do you think that's an important feature to have in this kind of app?

P1: I think definitely in terms of radiation. Someone to just you know verify things and things that are happening.

Interviewer: Okay, all right. Well there is a feature there so if you still want to check with us about anything you're more than welcome. Yeah, I'm going to take a look now. Okay, and then lastly there was a journaling feature. So what do you think about journaling? Fortunately it's difficult for me to journal if you guys.

6:13

P1: I will journal when I remember. Okay, and then like. It's a little difficult. Yes, and then like what would you, do you think it's easy or it's a stress relief to write down something or like what is your perception of journaling?

P1: It's not difficult to do, it's really nice to do actually. But like I said, I think my pregnancy brain is just so difficult to remember.

Interviewer: Is there anything else do you think that's going to make this app better?
P1: I think it's obviously in a beta stage now, but I think just if more people knew that there was such an app. Yes, and how do you think we can get it out there to the radiography community on Facebook and I think word of mouth as well. Okay, all right, yes. 1

8:55

Okay. Okay. But thank you so much, I really appreciate it. And all the best.

INTERVIEW 2

0:06

Interviewer: So, you think some days you were busy and you forgot to record? Yes. Okay, all right. And then tell me, so every day when you looked at your dosimeter, did you have a dose that you could easily see an input?
P2: Not really. Most of the days it was just at zero. Okay.

0:42

P2: Yes. When you were speaking, I felt like I wasn't confident. I was just like, somehow I wasn't using it correctly. All right, okay, so there's still that challenge that the dosimeter is, you know, not being used correctly.
Yes.

0:57

Interviewer: Okay, all right. And then tell me, did you see the other things on the app, like the explore features, whereby there's guidelines, education?
P2: Yes, I saw the articles. All right, and what do you think of it?honestly I didn't read it. Radiographers are very busy. I was just going through the moves that time.

1:29

Interviewer: Yes, yes, I can imagine. I just scrolled down and I zoomed everything. It was informative. So do you think that I know you received the app when you were

quite like far in your pregnancy do you think that maybe if someone is using the app from the early stages they will have more time to go through everything?
P2: Yes, definitely. Because now if you start using it at the early stages of your pregnancy. You have the whole of nine months to look at the articles, read everything, and learn the app.

2:12

Interviewer: Yes. I like that you're saying learn the app. Do you think that's important?
P2: Yes, it's very important to learn the app, because now, at first, for me, I struggled a lot, because I was struggling with downloading at first. So now if you start early, you get through and tackle those challenges earlier. Yes. And how do you think we can help you learn the app better?

3:41

Interviewer: Got nine months to actually figure the whole thing. Okay, all right, great. And then lastly, you saw that there was, did you see there was an expert, find an expert?
P2: Yes, I saw the medical physicist. Yes, yes. And did you not want to speak to the physicist when you were stuck with the dosimeter? I would say the problem is when I'm working, at that time they were busy renovating the building and stuff.

4:14

P2: So there was a time whereby I was not working, but I was able to use the app at some point because yeah. So sometimes I'll just be like, okay, you know, and not do anything about it. Yes, I get you.
Interviewer: Okay. And then lastly, there were features that is said to improve your emotional and mental health well-being, like mindfulness. There was links to that, mindfulness and journaling.

4:49

Interviewer: The mindfulness practices, did you manage to get there?

P2r: No, I didn't see those ones. I know.

Interviewer: Yes, the journaling, when I saw it, I... What do you think about journaling?

5:20

Interviewer: Yeah, I think it would be necessary to put in the app because as radiographers we go through the most, especially with our work. So, we just kept telling our feelings there, how the day went, and how the work as a whole is going as a radiographer.

5:56

P2: So, I think it's very important.

Interviewer: All right, great. And then lastly, I want to know from you, like any recommendations that you can have about the app, you know, even if it's something that, you know, it's very far-fetched, but any recommendations that can make it better.

6:19

P2I think because you know like sometimes we can be very busy, we get tired also, maybe we can have something like a notification on the phone where it reminds you to record your thing on your dosimeter. very helpful because it will remind us to fill in our recording. If you don't record, it means you're not doing anything with the app. Yes, and you lose that day on your dosimeter, right? Yes. So if we get notifications on the phone from the app, I don't know how you would do it but...

Interviewer: Yes, no, no, definitely it's possible. And just out there, what do you think of the phone as a dosimeter itself?

7:24

P2: I think it would be very, it would be great. It would be a very useful feature because now, like our phones, we have our phones everywhere we go, everywhere in the department, wherever we go. So sometimes they say, okay, we are supposed to wear our dosimeters wherever we go and every day, but I feel like a phone is more, compared to a dosimeter, I feel like a phone is much better. You look for your phone, not your dosimeter first. Yeah, yeah, yeah. We always have our phones with us. All right. Yes, yes, that's true.
there.