Textile Design for Diagnostic X-ray Shielding Garments and Comfort Enhancement for Female Users

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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July 2017
Declaration

I certify that except where due acknowledgment has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and ethics procedures and guidelines have been followed. I acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship.

Huda Ahmed M Maghrabi

July 2017
Dedication

This thesis is dedicated to my parents; to my father, Ahmed Mohammed Maghrabi, this is for you. Also for my mother, Aminah Salman Alqurni (my childhood teacher and loving mentor) – God have mercy on them. I hope you both rest in peace. For their kindness, devotion and unconditional love, they will always be remembered. I have never forgotten your words.

Also, this thesis is dedicated to my beloved kids, Asal, Ahmed, Joud and Youseef, for their endless love, caring and support. Thank you for your encouraging words and limitless faith in my abilities. You have created the right atmosphere for me to bring this research to fruition.
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List of Publications

The present work incorporates seven manuscripts, all have been peer reviewed and published or are in press in academic journals, as indicated below:

Journals


5. **Maghrabi, H., Wang, L., Vijayan, A. and Deb, P.** 2017 ‘Antimony Pentoxide and Bismuth Oxide Coating on Knitted Fabrics for X-ray Shielding’ *Journal of Industrial Textiles*, the paper is under review.

Conferences


### List of Abbreviations

<table>
<thead>
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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AOTI</td>
<td>Accumulative one-way transport index</td>
</tr>
<tr>
<td>BaSO₄</td>
<td>Barium sulphate</td>
</tr>
<tr>
<td>Bi₂O₃</td>
<td>Bismuth (III) oxide</td>
</tr>
<tr>
<td>BN1</td>
<td>Sample has coating formulation of (g) 100 PVC + 30 BO</td>
</tr>
<tr>
<td>BN2</td>
<td>Sample has coating formulation of (g) 100 PVC + 30 BO</td>
</tr>
<tr>
<td>BO</td>
<td>Bi₂O₃</td>
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<tr>
<td>BP1</td>
<td>Sample has coating formulation of (g) 100 PVC + 100 BO</td>
</tr>
<tr>
<td>BP2</td>
<td>Sample has coating formulation of (g) 100 PVC + 100 BO</td>
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<td>BP4</td>
<td>Sample has coating formulation of (g) 100 PVC + 200 BO</td>
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<tr>
<td>BS</td>
<td>BaSO₄</td>
</tr>
<tr>
<td>BSN1</td>
<td>Sample has coating formulation of (g) 100 PVC + 20 BS</td>
</tr>
<tr>
<td>BSN2</td>
<td>Sample has coating formulation of (g) 100 PVC + 40 BS</td>
</tr>
<tr>
<td>BSON</td>
<td>Sample has coating formulation of (g) 100 PVC + 20 BO +30 BS</td>
</tr>
<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>EL</td>
<td>Earth-Lite</td>
</tr>
<tr>
<td>Eu₂O₃</td>
<td>Europium (III) oxide</td>
</tr>
<tr>
<td>K</td>
<td>100% Kevlar plain woven fabric</td>
</tr>
<tr>
<td>keV</td>
<td>Kiloelectron volt</td>
</tr>
<tr>
<td>KvP</td>
<td>Kilo-voltage peak</td>
</tr>
<tr>
<td>KW</td>
<td>Kevlar/wool weft knitting single jersey</td>
</tr>
<tr>
<td>mAs</td>
<td>Milliampere second</td>
</tr>
<tr>
<td>MeV</td>
<td>Megaelectron volt</td>
</tr>
<tr>
<td>mmHg</td>
<td>Millimetre of mercury</td>
</tr>
<tr>
<td>MMT</td>
<td>Liquid moisture management tester</td>
</tr>
<tr>
<td>N</td>
<td>100% nylon plain woven</td>
</tr>
<tr>
<td>NW</td>
<td>Nylon/wool weft knitting single jersey</td>
</tr>
<tr>
<td>P</td>
<td>100% polyester plain woven fabric</td>
</tr>
<tr>
<td>PC</td>
<td>50% cotton 24% modal 24% bamboo 2% polyester weft knitting double jersey</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinylchloride</td>
</tr>
<tr>
<td>R_{ct}</td>
<td>Thermal resistance (m².k/w)</td>
</tr>
<tr>
<td>R_{et}</td>
<td>Water evaporative resistance (m².pa/w)</td>
</tr>
<tr>
<td>RL</td>
<td>Regular lead</td>
</tr>
<tr>
<td>Sb₂O₅</td>
<td>Antimony pentoxide</td>
</tr>
<tr>
<td>SID</td>
<td>Distance from X-ray beam source to fabric</td>
</tr>
<tr>
<td>SnO₂</td>
<td>Tin (IV) oxide</td>
</tr>
<tr>
<td>UL</td>
<td>Ultra-Lite</td>
</tr>
<tr>
<td>WinXCom</td>
<td>A program or data set based on the mixture rule</td>
</tr>
<tr>
<td>WO₃</td>
<td>Tungsten (VI) oxide</td>
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Abstract

X-rays are a useful diagnostic tool in the radiology world. Despite their usefulness, overexposure to radiation affects the health of those who are working closely with X-ray scanning equipment. Overexposure to high levels of radiation can cause large number of cells in the human body to die or to lose their ability to replicate. This damage can ultimately lead to organ failure. Currently lead aprons are the only primary protective garment used by radiation workers in hospitals and clinics to shield them from radiation. However, the commercial lead aprons currently available in the healthcare market have many problems; for example, causing user back pain due to the weight of the apron. These inflexible aprons can crack, compromising the user’s protection from radiation leakage, and the disposal of these aprons can pollute the environment due to the toxicity of lead. Also, commercial aprons at present are only available as a universal design for both males and females, and therefore are not designed to fit the female anatomical structure. This research aimed at developing a durable, safer and lighter textile substrate and garment structure that improves shielding and structural integrity.

In this thesis, the comfort properties of lead aprons have been evaluated to establish a baseline for future assessment of new designs. The thermal resistance of commercial lead aprons is shown to be high, potentially affecting the heat stress of the wearer. A new method was developed to measure the pressure distribution of lead aprons as part of understanding the comfort performance of protective clothing.

A range of textile fabrics that could be used as alternative casing for lead aprons were investigated with a view to enhancing the comfort properties of existing commercial products. Prototype aprons were developed to accommodate the different body shape of female radiographers with enhanced comfort properties. The prototype aprons will be used as a backing base for coating with non-lead-based X-ray absorbing substances that have the same shielding efficiency as the lead standard, but are safer for the environment and lighter in weight. Experimental results of fabric coating showed that microparticles of size less than 10 $\mu m$ and resin can be homogeneously spread on the coating side of the fabric surface. When the coating is on one side of the garment and primarily on the surface of the fabric, the uncoated fabric side can be exposed as the surface of an apron. This may save half the weight of casing material for an apron.
Different methodologies and woven and knitted textile substrates were used to develop coated materials with novel X-ray attenuating substances. This thesis found that the X-ray attenuating substance atomic number, density, mass attenuation coefficient, linear attenuation coefficient, atomic cross-section and other important factors can affect the attenuation strength and should be considered when designing X-ray shielding garments. As a result, the selection of radiation-absorber substances must be made carefully to combine all these properties. Bismuth oxide was one of the best selections and achieved the best result for shielding from X-rays.

Novel prototype aprons were developed based on evaluation of the benchmark lead aprons in terms of comfort performance. The selected textile materials have reasonable flexibility and good overall moisture management properties through use of a wool yarn plated with nylon. Different designs were created to suit the needs of various female bodies, such as radiographers, pregnant women and female patients who are undergoing mammography. All the prototype aprons have been assessed for comfort properties such as fit and air gap size, thermal comfort, stiffness and durability. It was found that the prototype aprons show enhanced comfort performance compared to the benchmark.
Chapter 1: Introduction

1.1 Background

In recent years, as the diagnostic scope of many medical facilities has expanded, the exposure to radiation from X-rays, CAT (computerised axial tomography) scans, fluoroscopy, gamma rays and radiation therapy has increased. Employment in the radiology field is projected to grow 21% from 2012 to 2022, faster than the average for all occupations [1]. The rapid technological developments related to medical equipment using radiation have prompted increasing concern for individual radiation protection and safety. Many studies on medical radiation shielding have been conducted because of the hazards that radiation presents to patients as well as health workers [2].

Lead-based material has been used for radiation protection for more than 100 years in several areas, especially for protection from X-rays. Lead shielding has been used for X-ray shielding because of its high atomic number, high density, high mass attenuation coefficient, long-term use and widespread knowledge of its use [3]. Radiation shielding uses lead equivalence as a measure of the X-ray attenuating ability of shielding garments [4]. Lead equivalence compares a shielding garment to pure lead. The unit of this measurement is millimetres in thickness. Benchmark lead-based aprons are prepared from lead oxide mixed with plasticisers or binders to make sheets, then used as protective apparel [5].

Despite the many advantages of using lead shielding sheets for radiation protection, lead garments have been proven to be associated with many problems. For instance, lead aprons can develop cracks, holes, rips and tears due to their inflexibility, causing radiation leakage and compromising the necessary protection [6, 7]. Another issue associated with lead garments is the toxicity of lead. The heavy use of lead in industrial processes has resulted in the deposition of large quantities of lead into the environment. Some uses of lead have been banned or limited in a number of countries including the United Kingdom, Canada and the United States of America [8].

Commercial lead aprons and other medical protective clothing made of different materials should not induce thermal discomfort. Although protection comes first, thermal comfort is secondary but still a priority. Discomfort experienced by surgeons can decrease their psychomotor skills and adversely influence the way that a medical
procedure is carried out [9]. Many musculoskeletal problems have been documented describing physical discomfort, in particular, neck, shoulder and back pain, due to the weight of these lead protection aprons.

The current lead aprons available in the market have only one design for both male and female workers; they are differentiated only in the length of the aprons. The design part of this research plays an importance role for enhancing the fit and comfort of female body structure. As a result, the worker can wear the newly designed apron for an extended period with comfy feeling since this apron achieves two main goals the fit and comfort, and protection against radiation. This research work has developed a unique design to protect sensitive tissues and important organs such as breasts and pelvic areas from unnecessary or scattered radiation exposure to suit the female body shape.

1.2 Research Aim and Objectives

This research aims at developing a durable, safer and more flexible textile for the radiography field, where an advanced textile substrate used as a backing material for the apron provides better structural integrity and X-ray radiation shielding. The prototype aprons using non-lead X-ray absorbing substances are lightweight, flexible, durable and designed to accommodate different body shapes for female users, while enhancing comfort properties.

The objectives of this research are:

- To study and understand the X-ray shielding mechanism and attenuation factors of textiles in relation to shielding and protection, and help to and select the best absorbers for X-ray radiation attenuation.

- To investigate and evaluate the existing lead apron materials for radiation shielding ability, fit and thermal comfort properties using different test methods. This objective will evaluate commercial aprons from different aspects including comfort, weight, fit, thermal comfort, pressure distribution, etc. It will also redesign and re-engineer the apron based on the data collected from these investigations.

- To develop and examine advanced garments for X-ray shielding using environmentally friendly metal chemicals – radiation absorbers as alternatives of toxic lead. This objective focuses on developing an efficient X-ray shielding garment
to replace the lead material with light weight and resistance to crack development by using environmentally friendly substances. This objective is related to the first objective for building an understanding around the area of X-ray protection and X-ray interaction with materials.

- To engineer and design 3D seamless female prototype aprons with improved fit and thermal comfort to offer more X-ray protective garments. This objective can be considered as the steps of design, assessment, engineering and study of aprons.
- To compare and assess the developed female prototype aprons with existing lead aprons for radiation-shielding requirements, fit and thermal comfort performance. This objective demonstrates the improvement in term of X-ray shielding, using alternative substances to toxic lead, less weight, and design of new aprons with enhanced fit and thermal comfort.

1.3 Research Questions

1. How can textiles help to enhance radiation shielding ability/durability?
2. What is the comfort level of the commercial lead aprons?
3. How should female prototype aprons be designed and engineered with enhanced thermal comfort and fit performance?
4. What are the alternative chemical-radiation absorbers for X-ray protection?
5. How can X-ray attenuation of coated protective clothing be predicted?
6. Do the newly developed female prototype materials meet the shielding requirements?

1.4 Significance of the Study

As the population grows older, there will be an increase in medical conditions, such as breaks and fractures caused by osteoporosis, which require imaging in order to be diagnosed [1]. The use of ionising radiation as a diagnostic and therapeutic tool is expected to increase further. The accompanying risks and effects of radiation exposure bring the need to protect patients and staff from the radiation hazards presented. Lead-based aprons are the current protective gear used by radiographers. These aprons could have many defects, which require solutions. In this research study, some of the
main defects have been addressed. The most important issue covered is the use of alternative metals as radiation absorbers for X-ray protection, rather than lead. Also, the heavy weight of the current lead aprons has been addressed. Some of our prototype samples have successfully achieved the same shielding efficiency with less weight. The comfort of commercial lead aprons has also been evaluated in order to help to design new prototype aprons with improved comfort properties. Lastly, comfort performance has been enhanced in many aspects with our new prototype aprons.

The findings of this research can become a reference for the radiology world and the medical field in general with the aim of reducing the weight and improving the comfort of X-ray protective garments. The results described can be used as a reference to identify the important factors that affect the durability of shielding garments and comfort performance in the market. Since the requirements for protective clothing such as lead aprons are increasing, the comfort of this type of protective gear must be enhanced to keep up with customer expectations. The prototype aprons might require more tests and future work to explore their commercial feasibility. We believe that this work can be continued and be of assistance to the defence and medical field workers who may be exposed to harmful radiation.

1.5 Thesis Overview

The peer-reviewed publications listed on preliminary pages xiv and xv comprise the individual chapters of this thesis. The text that appears in these chapters has been slightly modified from the original manuscripts. The formatting and numbering of headings, subheadings, figures, tables and equations have been altered for the purpose of amalgamation and consistency, to form the present thesis. The underlying theme that has guided the research in this thesis is the development of X-ray shielding materials.

Chapter 1 gives a general introduction to the topic and provides the background and guidance for the entire research framework.

Chapter 2 reviews previous studies on different aspects of the research problems. Related research reports on the investigation of X-ray shielding material garments, while commercial lead aprons and their common defects are reviewed and discussed. The literature on X-ray shielding garments and their comfort is analysed in depth. This
Chapter has resulted in a paper published in the proceedings of the TIBS Conference 2015 in Zadar, Croatia.

Chapter 3 elaborates on the laboratory-based experiments and methodology adopted to achieve the aims and objectives. It describes the apparatus, test instruments and facilities employed during this thesis work.

Chapter 4 is a study of the comfort and shielding performance of a selection of textile materials proposed as casing textile fabrics for commercial lead aprons. This chapter comes from two publications, the TIBS Conference 2016 in Melbourne and the *Journal of Fiber Bioengineering and Informatics* (JFBI) 2017.

Chapter 5 is an investigation of benchmark commercial lead aprons in relation to their comfort. The testing included thermal and water vapour resistance on standing manikins (in calm conditions), air gap, fit and pressure performance. This chapter is based on a paper submitted to the *Journal of the Textile Institute* (JOTI) 2017.

Chapter 6 covers the design, engineering and comfort assessment of the knitted 3D seamless female panel. The testing included thermal and water vapour resistance on standing manikins (in calm conditions), air gap and fit performance. The work in this chapter has been published in the proceedings of the International Design Technology Conference (Destech) 2015 in Melbourne.

Chapter 7 evaluates the shielding and protection performance of textiles coated with alternative chemical-radiation absorbers applied using various coating methods. This chapter has produced one publication in the *Textile Research Journal* (TRJ) 2016, and one publication in the *Journal of Fibers and Polymers* (FIPO) 2016. One manuscript has also been prepared and submitted to the Journal of Industrial Textiles (2017).

Chapter 8 outlines the conclusions that have been drawn from this research work, plus recommendations for further areas of study.
Chapter 2: Literature Review

2.1 Historical Foundation of X-ray Shielding

During the early part of the 20th century, the hazards from ionising radiation were recognised and the use of lead and other materials became commonplace for shielding against X-rays [10]. Since the risks of X-rays were considered, lead became an important material for radiation protection. In the last decade, shielding requirements have become more stringent as standards due to the observation of the catastrophic effect on human being relating to exposure of personnel and the general public have been reviewed [11, 12]. When dealing with X-rays, a dose ‘as low as reasonably achievable’ is practised, so that the radiation dose received by radiology personnel and the general public can be as low as possible [3].

In recent years, as the diagnostic scope of many medical facilities has expanded, the exposure to radiation from X-rays, computed tomography (CT), fluoroscopy, positron emission tomography (PET), gamma rays and radiation therapy has increased. Employment in the radiology field is projected to grow 21% by 2022, faster than the average for all occupations [1]. As the population grows older, there will be an increase in medical conditions, such as bone breaks and fractures caused by osteoporosis, which require X-ray imaging for diagnosis [1]. Hence, the use of ionising radiation as a diagnostic and therapeutic tool will increase. The accompanying risks and effects of radiation exposure will prompt the need of safer and comfortable garment to protect patients and staff from radiation hazard.

In the attenuation of radiation, metal particle size plays a significant role, so researchers have studied the effect of particle size on X-ray attenuation. To start with, they have examined metal nanostructured materials; for example, bismuth, copper and gold, which are materials whose single structural unit has a characteristic dimension between 1 and 100 nm [13]. Since the structural unit is smaller than those of most common materials, nanostructured materials exhibit unique physical and chemical properties for absorbing more X-ray photons, thus offering new application possibilities [14, 15]. In fact, some nanostructured materials have been successfully included in a polymer matrix for X-ray and gamma ray shielding [16, 17]. Examples of potential radiological protective garments made with nanostructured materials include bismuth, barium,
Nanoparticles can be dispersed uniformly in a matrix. For example, an average grain size of 13.4 nm of copper oxide (CuO) within a matrix showed less agglomeration when compared to larger sized particles; this contributed to a better attenuation ability via changes in the density and composition of the material [17, 19]. The X-ray spectra transmitted through a sample containing 30% CuO of both nano-sized and micro-sized particles for an incident X-ray beam of various energies; however, the nanostructured samples absorbed more photons as compared to the microstructured samples at 26 and 30 kV tube voltages. No significant absorption difference has been observed between low and high tube voltages [15, 20].

This chapter reviews and provides background information on the common issues associated with lead aprons used by medical personnel. It also reviews the attenuation of X-rays, the design of X-ray shielding materials, as well as the importance of understanding and utilising the science of X-ray interaction with matter.

2.2 Attenuation Properties of Diagnostic X-ray

Attenuation is the reduction in intensity of a radiation beam, in this case an X-ray, as the beam propagates through a material. The reduction may be caused by absorption due to the material, or by photons scattering or being deflected off the beam when hitting the particles in the material [13, 15]. Another kind of photon–matter interaction involves the atoms of the material absorbing the photons and being re-emitted thereafter [15, 16].

2.2.1 Factors affecting attenuation

Attenuation is dependent on material properties including density (mass attenuation coefficient), thickness (linear attenuation coefficient (μ)) and effective atomic number (Z_{eff}) number, which represents the total number of electrons surrounding the nucleus of a metal atom in a metal complex. It is composed of the metal atom's electrons and the bonding electrons from the surrounding electron-donating atoms and molecules [21]. A higher Z results in higher attenuation or absorption; all of these factors are correlated positively with the attenuation strength. Table 2-1 shows the linear attenuation
coefficient (thickness) for some selected materials. It is worth noting that the main contribution to X-ray attenuation is from the high atomic number of the materials. Added to that, the material thickness and mass have significant effects on the attenuation strength, because there is greater distance for the X-ray photon to travel through the medium.

Table 2-1 Physical properties of selected materials [22]

<table>
<thead>
<tr>
<th>Material</th>
<th>Effective Atomic Number (Z)</th>
<th>Density (g/cm³)</th>
<th>Linear Attenuation Coefficient at 50 keV (cm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>7.4</td>
<td>1.0</td>
<td>0.214</td>
</tr>
<tr>
<td>Ice</td>
<td>7.4</td>
<td>0.917</td>
<td>0.196</td>
</tr>
<tr>
<td>Water vapour</td>
<td>7.4</td>
<td>0.000598</td>
<td>0.000128</td>
</tr>
<tr>
<td>Compact bone</td>
<td>13.8</td>
<td>1.85</td>
<td>0.573</td>
</tr>
<tr>
<td>Air</td>
<td>7.64</td>
<td>0.00129</td>
<td>0.00029</td>
</tr>
<tr>
<td>Fat</td>
<td>5.92</td>
<td>0.91</td>
<td>0.193</td>
</tr>
</tbody>
</table>

Attenuation can also be dependent on the properties of the radiation beam, including its energy and the number of photons in the beam. Figure 2-1(a) shows the variation in intensity versus thickness of two materials. Material A has a greater atomic number (Z) than material B; therefore, less thickness of material A is needed to reduce the intensity to any chosen value. Figure 2-1(b) demonstrates the effect of radiation energy on X-ray attenuation. As photon energy increases, the attenuation produced by a given thickness of absorbing material decreases. Figure 2-1(b) also shows the variation in intensity versus thickness for two beams. Beam 1 \( (E_1) \) is of greater energy than beam 2 \( (E_2) \). The lower energy beam is attenuated more rapidly by a chosen thickness of absorbing material [23].

![Figure 2-1 (a) Effect of atomic number on X-ray attenuation; (b) Effect of radiation energy on X-ray attenuation [23]](image-url)
For all materials, the density and the K-absorption edge are two important factors affecting the material attenuation efficiency [24]. The absorption edge is the energy at which there is a sharp rise (discontinuity) in the (linear) absorption coefficient of X-rays by an element, which occurs when the energy of the photon corresponds to the energy of a shell of the atom (K, L_I, L_{II}, L_{III}, etc.) [3].

2.2.2 X-ray interactions with matter

In radiological physics, five common types of X-ray interactions should be taken into consideration. The values of mass attenuation coefficients are dependent on the absorption and scattering of the incident radiation caused by several different mechanisms:

I. Photoelectric effect
II. Compton scattering effect
III. Pair production
IV. Rayleigh scattering
V. Photodisintegration

Importance should be given to the photoelectric effect, Compton scattering effect and pair production, as they impart energy on the material along the photon track (see Figure 2-2). These three interactions are dependent on the energy of the photon E (hv) and the effective atomic number Z of the absorbing material, except that Compton scattering is independent of Z. Figure 2-2 displays the region E (hv) and Z together with the dominance of each interaction. The photoelectric effect (PE) region is dominant at low photon energy, Compton scattering is dominant at intermediate photon energy and the pair production (PP) region is dominant at high photon energy. Furthermore, the Compton scattering effect has a larger significance for lower Z materials than those with higher Z [18]. Figure 2-2 shows the behaviour of these three major photon interactions with matter, specifically: photoelectric effect τ, Compton scattering effect σ and pair production κ [18, 19]. The best selection of shielding materials for attenuation purposes are those with high effective atomic numbers but low densities [20].
2.3 Types of Commercial Lead Aprons for X-ray Shielding

2.3.1 Lead vinyl

Most commercial protective aprons that are used to shield radiographers from radiation contain lead particles and often other metals; for example, bismuth, barium, tungsten, tin and antimony [21, 22]. The metals are uniformly mixed with polyvinyl chloride (PVC), synthetic rubber pigments, stabilisers and plasticisers to make thin sheets. An apron is made from two to five thin sheets covered by nylon fabric coated with urethane on the side against the sheets. These protective garments attain different durability, weight, radiation absorption efficiency and flexibility by varying the grades of PVC or rubber, proportion of metals, mixture of metals and number of sheets [21]. Such aprons are resistant to abrasion, acid and alkali, and are easy to clean. The protection provided by this type of sheeting is compared with that of pure lead and referred to as ‘lead equivalence’ [22]. The shielding capability is directly related to the thickness of the shielding material [23]. Table 2-2 shows an example of the relationship between lead vinyl thickness and lead equivalence shielding value.

<table>
<thead>
<tr>
<th>Lead vinyl thickness (mm)</th>
<th>Lead equivalence shielding value (mm) Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>0.25</td>
</tr>
<tr>
<td>1.6</td>
<td>0.50</td>
</tr>
<tr>
<td>3.2</td>
<td>1.00</td>
</tr>
</tbody>
</table>
2.3.2 Poly tungsten

Poly tungsten, also known as tungsten filled-polymer, can be used to make radiation-protective sheets, curtains and clothing due to the high atomic number (Z=74) and high density (19.3 g/cm³) of tungsten. Tungsten is known to be less toxic than lead at low levels [25] and provides better radiation shielding, with no leakage or hot spots compared to lead [26]. The resins used to produce poly tungsten include, but are not limited to, acrylonitrile butadiene styrene, polyamide, polyurethane and thermoplastic elastomer. In addition, the raw material for the production of poly tungsten is non-toxic and recyclable. Poly tungsten is pliable and easy to cut, hole and shape [26, 27].

2.3.3 Demron fabric shielding

Demron fabric shielding was produced by sandwiching PVC-based polymers or polyethylene between two woven fabric layers [28]. The shielding fabrics have been produced using matrices made of resin, nano and micro-scale metallic particles. The particles are made to fuse and interlock with the fabric. This provides protection against ionising radiation. Compared to lead, this type of fabric is light and non-toxic, and hence applicable to producing radiation-proof tents and aircraft linings. Unlike traditional materials used to make medical aprons, however, Demron fabric can develop crack when it is folded due to its stiffness and multilayers. In terms of radiation shielding, a Demron suit can provide shielding from energetic beta particles and 50% shielding against gamma rays of less than 130 keV [29].

2.3.4 Anti-radiation underwear and swimsuits

Yamamoto Corporation, a Japanese company, has produced a full-body wetsuit-style garment made from a biorubber material that contains microscopic bubbles which deflect almost 100% of beta particles [26]. The design as swimwear is to protect the wearer from radioactive water. It can be used by emergency workers who are trying to clean up waste from nuclear power stations. Alternative products made from such material could be of more general appeal. The company has also created a line of anti-radiation underwear made from a lead-infused fabric. It is designed to protect the wearer’s pelvic and lower spine area. The underwear is claimed to almost completely block gamma rays and all lesser forms of ionising radiation. However, these undergarment products are bulky and weigh nearly 3.5 kg [27].
2.4 Lead Aprons as Protective Garments: Shielding Issues

2.4.1 Cracks, holes, rips and tears

A typical lead-impregnated vinyl apron consists of an outer nylon or polyester fabric [28]. Aprons in hospitals are subject to abuse and misused in normal wear, which leads to with time developing tears and cracks while in use. They are sometimes folded, dropped or creased in a manner that causes the vinyl to bend. Consequently, lead-impregnated vinyl aprons may deteriorate and begin to form holes and cracks [28]. These cracks and holes can be observed radiographically or fluoroscopically by exposing the apron to X-rays. According to the Joint Commission on the Accreditation of Healthcare Organizations (JCAHO), it is a requirement for radiation health and safety that aprons are inspected on a yearly basis. There is no particular limit for how long the aprons can be used; they may last up to 10 years. The testing for imperfections in an apron can be achieved by fluoroscopy on a floating-topped table or by radiography. Any cracks or holes found should be marked and recorded. To reduce costs, a lead apron may only need to be replaced if a defect is greater than 15 mm² in areas close to critical organs and, for areas at the back or along the seams, replacement only if a defect is greater than 670 mm² [29].

Figure 2-3 ‘Picture gallery’ of defects including crack (a,b), rip (c) exceeding 670 mm² and tear (d) on the lead aprons as seen on the X-ray films [7, 30]
Defective lead aprons are a major problem in many hospitals, with immense health implications. It is reported that a substantial proportion of lead aprons used in hospitals did not meet the standard requirements [36-39], such as the International Electrotechnical Commission Standard IEC 1331-1 (1994) protective devices against diagnostic medial X-radiation [40]. A recent study by Oyar and Kislalioglu [38] established that 20% of manufactured lead garments were incapable of absorbing radiation. Furthermore, 68.2% of aprons were found to be defective. The defects included cracks, rips, holes and tears, as shown in Figure 2-3. Similar studies emphasise the importance of regular inspection of aprons in use to check for any defects that occur due to misuse. Another study by Finnerty and Brennan [39] established that 73% of the aprons used by one institution were not within tolerance levels, even though they were labelled otherwise.

A recent study done by Oppliger-Schäfer and Roser [41] indicated that 1 in every 5 lead aprons tested had defects in its protective layers. The defects ranged from insignificant (undetectable) to severe. According to the researchers, most defects were detected in departments that regularly used X-ray equipment. These departments included cardiology, angiography and urology. Different types of defects were observed in garments that were frequently used such as aprons, vests and skirts. Oppliger-Schäfer and Roser [41] also used fluoroscopy and a combination of visual inspection and palpation to examine the aprons in their study. They identified critical spots and established that all protective garments were subject to defects irrespective of the type of material used and age. Hence, aprons with defect areas exceeding 670 mm² as seen in Figure 2-3(c) should be rejected [32, 42].

### 2.4.2 Toxic nature of lead material

Lead is widely used in medical radiology because of its ability to absorb or block X-ray radiation. The level of shielding against radiation depends on the thickness of the lead sheet. Pure lead metal cannot be worn as apparel because of its brittle nature. A protective sheet is prepared by mixing pure lead or its oxide with PVC or plasticisers. The lead is embedded in rubber or elastomer to make radiation-shielding material [43]. The materials are fused into curtains, covers and garments for radiation-protection purposes.
Lead is toxic to both animals and people. The toxicity varies according to the level of exposure. These toxic effects range from acute and symptomatic poisoning following high exposure levels to subclinical but still dangerous poisoning at lower exposure levels. Lead in its pure state is not metabolised in the body. Instead, it will be absorbed and moved around the body. Lead poisoning has effects on virtually every organ in the body. However, the cardiovascular, nervous, gastrointestinal, haematological, endocrine and renal systems are the most affected [44].

The heavy use of lead and other hazard substances in industrial processes and medical devices has resulted in growing mountains of waste and the deposition of large quantities of lead into the environment, causing damage [31]. Consequently, the use of lead has been banned or limited in a number of countries including the United Kingdom, Canada and the United States of America [45, 46]. However, lead sheeting and lead aprons are still primarily used for radiation shielding. It is expected that lead aprons will be phased out in the near future.

2.5 Lead Aprons as Protective Garments: Comfort Issues

2.5.1 Thermal comfort

Thermal comfort as a component of overall comfort is a complex sensation that is influenced by physical, physiological and psychological factors. Thermal comfort integrates various different sensory inputs. This sensation is regarded as the driving force of behavioural thermoregulation [47]. Thermal comfort is determined by sensations of heat, cold and humidity. Surrounding temperature changes are perceived by the sensory cells on the skin. There are six main aspects that affect thermal comfort and these can be categorised into two groups: (1) personal factors, including metabolic rate and clothing insulation; and (2) environmental factors, which are conditions of the environment, comprising air temperature, humidity, air speed and mean radiant temperature [47, 48].

Clothing, apart from its effect on heat exchange, also affects metabolic rate, which can affect thermal comfort in turn. Humans have dissimilar metabolic rates that can fluctuate due to action levels and environmental circumstances [49]. The usual activities of a medical worker include standing, movement and walking. The added weight of a
lead apron increases the metabolic rate in human activity. Heavy ensembles are also associated with stiffness. Consequently, the wearer does additional work to overcome the stiffness. The extra work results in an increased metabolic rate [47, 50]. Clothing insulation has a significant impact on thermal comfort, because it influences the heat transfer and consequently the thermal balance. More layers of insulating clothing can prevent heat loss, either keeping an individual warm or leading to overheating.

Medical protective clothing made of different materials should not induce thermal discomfort. Such an uncomfortable sensation when experienced by surgeons can decrease their psychomotor skills and, at the same time, adversely influence the way that an operation procedure is carried out [51]. In this context, if a radiologist attempts to do an examination for more than 60 minutes, thermal comfort becomes an issue and can negatively affect their performance even though they usually perform the operations and procedures in air-conditioned rooms. The heavy weight of the aprons and multi-layered clothes underneath, as well the type of activity, will have an impact on their thermal comfort sensation and thus may cause discomfort.

Thermal comfort issues in protective clothing like lead aprons were assessed by Bodgan et al. [51]. The study was conducted on two surgeons in two operating theatres. Each surgeon was subjected to four experiments, adorned in different protective clothing that included a 0.5 mm lead apron. The measurements taken included the temperature and humidity. The researchers observed the heat insulation challenges experienced by the surgeons wearing different types of protective clothing, including lead aprons. It was noted that the thermal insulation of surgical underwear and lead gowns was lower than that of the ensembles with other surgical gowns such as disposable medical clothing and barrier surgical gowns for multiple use due to the weight of the lead gowns (3.3 kg) rather than their high insulation. Lower mean humidity in the area between the skin and clothing was observed during an operation when a surgical underwear and cotton gown were worn together with a lead apron. The most negative assessment of thermal environment was noted during the experiment with cotton gown and lead gown protection against X-rays.

2.5.2 Weight of commercial lead aprons

The heavy weight of lead aprons contributes to physiological disorders, such as neck/shoulder and back pain. Moore and Novelline [32] reported a relationship
between lower back pain and the weight of lead aprons used by radiologists. This is supported by other researchers who have established that extensive wearing of lead aprons may be the cause of back pain in radiologists [33].

The musculoskeletal regions of physical discomfort include the neck, shoulders and back; as shown in Figure 2-4. As lead aprons should be worn in the examination room by all workers in radiology, the length of time wearing the lead apron should be reduced to minimise physical discomfort and effects. In a survey study, back pain was reported by 52% of those who estimated their lead apron use at more than or equal to 10 hours per week, the mean response, as opposed to 46% of those who wore lead aprons fewer than 10 hours per week [32]. The study also found high rates of skeletal-related complaints among cardiologists who used lead aprons. Cardiologists reported a high number of work days lost due to pain and greater frequency of musculoskeletal complaints [35, 36]. The higher rate of discomfort reported by these cardiologists may be due to greater pressure generated within the spinal discs while supporting the weight of the one-piece suit directly through the shoulder girdle [37]. Some recommendations suggest the use of support belts to minimise the fatigue from wearing lead aprons for long periods. However, there is still no research evidence associating the use of back-belts with reduction in the risk of back pain [38, 39].
2.6 Lead Aprons as Protective Garments: Design Issues

The design of lead aprons has not changed significantly since they were invented more than 100 years ago. The term ‘apron’ historically refers to a sleeveless garment. The lead apron design has remained similar in characteristics over the years except for a few changes in colour, style, fasteners and material. The apron design has not undergone any significant safety modifications even though radiation-induced injuries have been reported since the early 20th century [10].

Radiation is a risk factor for increased incidence of cancers among healthcare staff working in radiology departments [40]. The US Radiologic Technologist Health Study observed between 1983 and 1998 an increased rate of breast cancer among female radiographers [61]. The study found that lead aprons provide no protection to the axillary region or the lateral aspect of the breast, especially in individuals with large breasts [62]. The leaded garment does not drape well over the breasts, the armholes or the arm openings on the apron. It leaves the breasts projecting forward, thereby increasing exposure of the chest area [63, 64]. To date there has been no significant improvement on the design side of lead aprons, in particular taking into consideration of the upper female anatomical structure.

Fit in relation to clothing encompasses both comfort and appearance. Functional ease is another requirement for protective garments. Functional ease refers to the ease with which a protective garment adapts to and accommodates the movement of the wearer while still maintaining its functional use. The fit of a protective garment lies in its capacity to balance the needs of the individual and its required functionality [65]. According to Boorady [65], a well-fitted garment should have no wrinkles when a person is standing still. General observation of commercial lead aprons is that they display vertical wrinkles, likely due to the stiffness and looseness of the apron, and this wrinkling requires reduction by overlapping or tucking (narrowing) the pattern to suit the body shape [66].

There is limited research quantifying the effectiveness of wearing a lead apron in terms of fit. For example, a pregnant woman undergoing an X-ray procedure is required to wear a specially designed maternity apron that covers her and protects her fetus from radiation, because radiation exposure is very harmful to fetuses [2]. Lubow [67] in 1950 and Hollands in 1962 established that the main focus for the apron was to cover the
important organs as a whole area, without considering natural female curves, leading to a poorly fitting design. In attempting to design a lead apron that has a good fit, some manufacturers use adjustable strapping, hooks, ties or loop tape. The tape can be used to decrease the fullness of the clothing in areas around the torso and arms [65]. Still, all current lead aprons fail to fit the natural curves of the female body. Furthermore, current lead aprons tend to decrease ease of movement for radiographers wearing a one-piece lead apron [69].

It is important to consider using alternative substances for absorbing X-rays, based on the understanding from the literature, that are more effective than toxic lead material and provide less weight at the same time. This gap is addressed in Chapter 4.

This research work, based on this intensive literature review, redesigns and re-engineers the current aprons to suit the curved female body structure using recent technology for body shape measurement, taking into consideration the ease of movement for the female worker and special areas like the breast, thyroid and abdominal areas, plus the pelvis area. This will ensure that all the radiosensitive areas are well covered by the garment shielding. The redesign issue is addressed in Chapter 5. The comfort performance of the current commercial aprons and the newly developed aprons has then been evaluated, using different test methods. This is illustrated in detail in Chapter 6.

2.7 Summary

Lead aprons have been used for almost a century to provide protection against X-ray radiation and they are still widely used for this purpose. The current lead apron is associated with many problems, like reduced effectiveness of protection and increased discomfort level. Defects in lead aprons like cracks and holes can leak radiation and cause overexposure to individuals. All these common defects are well recognised by researchers. Additionally, lead aprons are heavy and uncomfortable to wear. Their heavy weight is a cause of increasing musculoskeletal problems. Lead aprons cause physiological disorders that include neck, shoulder and back pain in radiologists. Poor fitting of lead aprons to the female body has also been associated with increased incidence of breast cancer among female radiographers. Similarly, poisoning from the lead material has prompted researchers to try and find alternative less toxic materials. These reviewed gaps point to the need for further research and investigation of
protective clothing with environmentally friendly X-ray absorbers to assess its
effectiveness in term of shielding, comfort and garment design to suit natural female
curvature.
Chapter 3: Experimental Work Undertaken

Chapter 3 describes the experimental methodology used together with the fabrics, chemicals, equipment and instruments, and relevant procedures employed in the course of the investigation.

3.1 Research Design

The prime objectives of this research were to develop a textile base as a substrate backing material for radiation-absorbing materials that was flexible, lightweight and more durable than current backing materials, and also environmentally friendly. Figure 3-1 outlines the experimental design.

Figure 3-1 Outline of the research plan
3.1 Textile Materials

3.1.1 Woven fabric

For the experiments, plain-weave fabrics of 100% nylon and 100% polyester were used as they both have good strength, resilience, light weight and durability. Both nylon and polyester fabrics are commonly used as casing materials for lead aprons. To demonstrate the concept of fabric-based X-ray shielding materials and comfort performance, different fibre types and fabric weights were considered for each. The specifications of the scoured greige fabrics are shown in Table 3-1.

Table 3-1 Woven fabric properties

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Polyester</th>
<th>Nylon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabric composition</td>
<td>100% polyester</td>
<td>100% nylon</td>
</tr>
<tr>
<td>Weave</td>
<td>Plain</td>
<td>Plain</td>
</tr>
<tr>
<td>Yarn</td>
<td>Filament</td>
<td>Filament</td>
</tr>
<tr>
<td>Fabric thickness (mm)</td>
<td>0.18</td>
<td>0.59</td>
</tr>
<tr>
<td>Fabric weight (g/m²)</td>
<td>149.2</td>
<td>315.4</td>
</tr>
<tr>
<td>Warp yarn count (tex)</td>
<td>29.25</td>
<td>103</td>
</tr>
<tr>
<td>Weft yarn count (tex)</td>
<td>32.85</td>
<td>99.15</td>
</tr>
<tr>
<td>Ends/cm</td>
<td>18.89</td>
<td>16.53</td>
</tr>
<tr>
<td>Picks/cm</td>
<td>16.53</td>
<td>12.99</td>
</tr>
</tbody>
</table>

3.1.2 Knitting fabric

For developing the knitted fabrics, 100% nylon and 100% wool yarns were selected. The selection was based on their yarn count in order to develop a plated knitted structure that could produce two different fabrics to have similar properties. The details of the yarns used in this study are presented in Table 3-2.

Table 3-2 Yarns for fabric engineering

<table>
<thead>
<tr>
<th>Fibre (100%)</th>
<th>Yarn count (tex)</th>
<th>Yarn type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nylon</td>
<td>94</td>
<td>Continuous filament</td>
</tr>
<tr>
<td>Nylon</td>
<td>120</td>
<td>Continuous filament</td>
</tr>
<tr>
<td>Wool</td>
<td>41</td>
<td>Spun, two-fold</td>
</tr>
</tbody>
</table>

A weft knitting structure was used for the experiments; this fabric was produced and developed to make a 3D shape for the female apron design. The purpose of using this type of yarn due to its strength was to help produce the fabric to apply a different level
of coating film on the surface of the front side. Fabrics with the same construction, but
different masses and thicknesses, were used in order to be suitable for the coating paste.
Also, both fabrics were greige in colour. The knitted fabric properties are listed in Table
3-3.

Table 3-3 Knitted fabric properties

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Yarn count (tex)</th>
<th>Wales (/cm)</th>
<th>Courses (/cm)</th>
<th>Fabric thickness (mm)</th>
<th>Mass per unit area (g/m²)</th>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nylon/wool</td>
<td>Nylon 94, Wool 41</td>
<td>8.6</td>
<td>6.2</td>
<td>1.37</td>
<td>524.6</td>
<td>Weft knitting single jersey</td>
</tr>
<tr>
<td>Nylon/wool</td>
<td>Nylon 120, Wool 41</td>
<td>7.4</td>
<td>10.2</td>
<td>1.35</td>
<td>473.8</td>
<td>Weft knitting single jersey</td>
</tr>
</tbody>
</table>

3.2 Chemicals Used in This Research

The sources of various chemicals used to coat the greige fabrics with radiation-
absorbing materials are listed in Table 3-4.

Table 3-4 Chemicals used and their suppliers

<table>
<thead>
<tr>
<th>Code</th>
<th>Name of material</th>
<th>Particle size</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi₂O₃</td>
<td>Bismuth (III) oxide</td>
<td>10 μm</td>
<td>Sigma Aldrich</td>
</tr>
<tr>
<td>BaSO₄</td>
<td>Barium sulphate</td>
<td>~1 microns</td>
<td>Sigma Aldrich</td>
</tr>
<tr>
<td>Sb₂O₅</td>
<td>Antimony pentoxide</td>
<td>0.04 μm</td>
<td>MARCHEM Australia Pty Ltd</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinylchloride</td>
<td>–</td>
<td>Union Inc., USA</td>
</tr>
<tr>
<td>Ptre-9000</td>
<td>Ptre-9000</td>
<td>–</td>
<td>Union Inc., USA</td>
</tr>
</tbody>
</table>

3.3 Greige Method

Woven fabrics were scoured using this method before applying the coating paste:

0.5g/L wetting agent
15g/L caustic soda (sodium hydroxide)
10 % sodium carbonate solution
1:10 liquor ratio
pH 10–10.5
3.4 Coating Method

3.4.1 Knife-edge coater

As an example of the coating method applied, the polyester and nylon fabric samples were coated using three different application levels of bismuth oxide (Bi$_2$O$_3$) and PVC resin using a knife-edge coater. For example, 30 g of Bi$_2$O$_3$ and 100 g PVC were mixed in a blender for 15 min. to become consistent. The mixture was then coated on fabric specimens using a similar amount of coating for each sample. Six different samples were coated using the formulation developed and the fabrics were dried at 60 °C and further cured at 150 °C in an oven for 5 min.

3.4.2 Mathis laboratory coating device (bar coater)

The Mathis device (see Figure 3-2) was also used for coating. The non-lead fabric samples were coated using different chemical components made up of three different applications levels of, for example, Bi$_2$O$_3$ and PVC resin, using a knife-edge coater, while another device used was a bar coater. For instance, one concentration was made up by mixing 100 g of PVC resin with 20 g of BaSO$_4$ and mixed in a blender for 15 min. to become consistent. The mixture was then coated on the fabric samples using a prescribed amount of coating for each sample to make a film. Four different samples were coated using the formulation developed and the fabrics were dried at 60 °C and further cured at 150 °C in an oven for 5 min. The same procedure was applied for the other samples.
3.5 Instruments and measurements

3.5.1 Instruments and testing methods

Table 3-5 Equipment and standards used.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Equipment and standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knitted fabric and apron production</td>
<td>Knitting machine Shima Seiki SES-S. WG® and its whole garment WG-SDS-one APEX3 program</td>
</tr>
<tr>
<td><strong>Fabric composition testing</strong></td>
<td></td>
</tr>
<tr>
<td>Wales and courses per unit length</td>
<td>Carson linen test 5× power, 30 mm lens stitch counting magnifier (LT-30) (AS 2001.2.6-2001)</td>
</tr>
<tr>
<td>Picks/ends per centimetre</td>
<td>Carson linen test 5× power, 30 mm lens stitch counting magnifier (LT-30) (AS 2001.2.5-1991)</td>
</tr>
<tr>
<td>Optical porosity</td>
<td>Motic Microscope and software Motic Images Plus 2.0 ML</td>
</tr>
<tr>
<td>Fabric structure analysis and SEM images</td>
<td>Microscope, FEI Quanta 200 ESEM (2002)</td>
</tr>
<tr>
<td></td>
<td>Microscope, Philips XL30 SEM (1999)</td>
</tr>
<tr>
<td></td>
<td>Optical Microscope, Leica digital image DM 2500 M, Leica Application Suite V 3.2.0 software</td>
</tr>
<tr>
<td><strong>Fabric physical and mechanical standard methods</strong></td>
<td></td>
</tr>
<tr>
<td>Mass per unit area</td>
<td>Laboratory balance, 3200g-Fz-3000i (AS2001.2.13-1987)</td>
</tr>
<tr>
<td>Thickness</td>
<td>Thickness tester (AS 2001.2.15-1989)</td>
</tr>
<tr>
<td>Abrasion resistance/mass loss</td>
<td>Martindale abrasion tester (AS 2001.2.25.3-2006)</td>
</tr>
<tr>
<td>Abrasion resistance/specimen breakdown</td>
<td>Martindale abrasion tester (AS 2001.2.25.2-2006)</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>Breaking force and elongation of textile fabric (strip method) ASTM D5035-11, Instron 5565A instrument</td>
</tr>
<tr>
<td><strong>Measurements testing (sizing and fit)</strong></td>
<td></td>
</tr>
<tr>
<td>Body size measurement and fit</td>
<td>Full body female manikin size 14 US</td>
</tr>
<tr>
<td></td>
<td>Full body pregnant manikin size 14 US</td>
</tr>
<tr>
<td></td>
<td>3D body scanner system made by Textile/Clothing Technology[TC]²</td>
</tr>
<tr>
<td>Air gap size measurement</td>
<td>CAD software</td>
</tr>
<tr>
<td><strong>Thermal comfort testing</strong></td>
<td></td>
</tr>
<tr>
<td>Thermal insulation and evaporative resistant for garment</td>
<td>Sweating thermal manikin, newton</td>
</tr>
<tr>
<td></td>
<td>Thermal DAC control software by MTNW (F1291-10) and (F2370-10)</td>
</tr>
<tr>
<td>Thermal and water vapour resistant fabric</td>
<td>Sweating Guarded Hotplate(SGHP), manufactured by SDL Atlas (ISO 11092:1993(E))</td>
</tr>
<tr>
<td>Moisture management test</td>
<td>Moisture Management Tester (MMT) instrument, manufactured by SDL Atlas (AATCC TM 195-2009)</td>
</tr>
<tr>
<td>Air permeability</td>
<td>Air permeability tester M021S, manufactured by SDL Atlas (EN ISO 9237.1995)</td>
</tr>
<tr>
<td><strong>Sensory comfort</strong></td>
<td></td>
</tr>
<tr>
<td>Pressure distribution</td>
<td>Innovative Pressure Mapping Solutions from Vista Medical Ltd</td>
</tr>
<tr>
<td>Stiffness of cloth</td>
<td>A 133 Shirley Stiffness Tester (AS 2001.2.9)</td>
</tr>
<tr>
<td>Stretch and recovery</td>
<td>Instron 5565A instrument (BS EN 14704-1:2005)</td>
</tr>
<tr>
<td><strong>X-ray exposure testing</strong></td>
<td></td>
</tr>
<tr>
<td>Determination of attenuation properties of materials</td>
<td>Medical X-ray machine (SHIMADZU X-ray system)</td>
</tr>
<tr>
<td>Total mass attenuation coefficient analysis</td>
<td>Software XCOM code</td>
</tr>
</tbody>
</table>
All samples were tested after conditioning for at least 24 hours under standard conditions of temperature (20 ± 2°C) and relative humidity (RH) (65 ± 2% RH), as specified in Australian Standard (AS) 2001.1-1995. The equipment and standards used in this research are listed in Table 3-5, where the testing is categorised according to the type of test applied.

### 3.5.2 Fabric physical and mechanical properties

Fabric physical properties that can influence comfort were tested. This included the type of material, fabric construction (weave and ends/picks per inch for woven fabrics and wales/courses per inch in knitted fabrics), mass per unit area and thickness. The number of wales and courses in a knitted fabric sample was counted along a line at right angles to the courses or wales being considered. Fabric samples were conditioned, and each was laid horizontally on a table with minimum tension to keep the fabric flat. The number of wales and courses was counted using a stitch-counting magnifier, avoiding the fabric edges [41].

#### 3.5.2.1 Picks/ends per centimetre

The number of ends and picks in a woven fabric sample was counted along a line at right angles to the yarn being considered. The lengths of fabric were chosen so that the number of threads counted, in each case, was not less than 50. Five samples from each fabric were tested. Five counts in each of the warp and weft directions were made, avoiding the selvedge of the fabric, using a stitch-counting magnifier [42].

#### 3.5.2.2 Optical porosity

An optical microscope was used to observe the surface morphology of the samples before and after the abrasion test. Digital images from light transmission were acquired via the multimedia software Motic Images Plus 2.0 ML.

#### 3.5.2.3 Fabric structure analysis and SEM images

A Philips XL30 Field Emission scanning electron microscope and Microscope, FEI Quanta 200 ESEM (2002) were used for the analysis of surface morphology of the coated
samples. Samples were prepared by coating them with gold using a sputter coater in an argon-purged chamber for 60 sec. Then the specimens were observed in the XL30 SEM chamber at a voltage of 30.0 kV and 10 mm working distance (WD). The magnification was set above 1500×.

3.5.2.4 Mass per unit area

Five specimens of each fabric measuring 100 mm × 100 mm were conditioned and tested in a standard atmosphere. Each specimen was weighed by a measuring balance. The mass per unit area was calculated using Equation 3.1 [43]. The arithmetic mean of five readings was reported.

\[
m_{\text{ua}} \ (\text{g/m}^2) = \frac{W}{A}
\]

Equation 3.1.

Where:

- \(m_{\text{ua}}\) is the mass per unit area of the fabric after conditioning in the standard atmosphere of testing, [g/m²]
- \(A\) is the area of the specimen, [m²]
- \(W\) is the mass of the specimen, [g]

3.5.2.5 Material thickness

The material thickness was measured according to the Australian Standard for measuring textiles, AS 2001.2.15. The arithmetic mean of five measurements was taken to determine the thickness [44].

3.5.2.6 Abrasion resistance, specimen breakdown/loss of mass

The AS 2001.2.25.2-2006 [45] and AS 2001.2.25.3-2006 [46] test methods were applied; a Martindale tester was used to perform the experiment. The diameter of the test specimens was cut to \(38^{+5}_{0}\) mm. The dimensions of the abradant were at least 140 mm in diameter or length and width. Polyurethane foam backing was used for each sample. The total effective mass of the abrasion load (i.e. the mass of the specimen holder
assembly) and the appropriate loading piece for apparel and household textiles (nominal pressure of 9 kPa) were given.

The weight of the samples were recorded before the test was applied and then after the set number of rubs. The breakdown of the test specimen was observed for each of the established levels of 5000 rubs and according to the levels at which specimen breakdown occurs. Breakdown was determined at the following number of rubs: 20 000. All samples were rubbed individually, and the arithmetic means for all samples were taken to determine the breakdown and mass before and after rubbing. Breakdown points were set for test intervals for the abrasion test for the test series from 5000 to 40 000 rubs. The mean of duplicate determinations on four samples was obtained for each sample. According to the standard [45] there are two approaches for assessment of abrasion resistance: first, to abrade the sample until a predetermined end-point is reached, such as the breaking of two threads in woven fabric or the generation of a hole in knitted fabric, while recording the time and number of cycles to achieve this. The second approach is to abrade for a set time or number of cycles and then assess the fabric for change in appearance, loss of mass [46], loss of strength, change in thickness or other relevant properties.

3.5.3 Body size measurement and fit

The models used for the 3D scanning of the manikin female body were three size 14 manikins of a pregnant female body, normal female body and (Newton) female body. A 3D body scanner system made by Textile/Clothing Technology (TC)² was used to develop an accurate representation of the female body figures and measurements. The readings, that is, the measurements taken from the manikins, were used to develop a comparison of the measurements of the (skin layer) unclothed manikin and the clothed manikin with uniform plus aprons for sizing and fit. The scans of the unclothed and clothed manikins were imported into CAD software for data processing.

One garment of each style was scanned three times to determine the reproducibility of the measurements. This garment was dressed on the manikin, a scan was taken, the manikin undressed, and then dressed again for the second and third scans. Because the size and distribution of air gaps were variable between scans and depended largely on how the manikin was dressed, changes in air gaps were minimised by following a
specific dressing protocol. This involved gently pulling downwards on the waist, seat, and sleeve and leg cuffs of the garments while on the manikin. Pictures of the dressed manikin were taken and compared across garments of the same style to ensure consistency of fit; the system was borrowed from Mah and Song [47]; see Figure 3-3.

![3D point cloud data and example: (a) unclothed front; (b) unclothed side; (c) medical scrub uniform front; (d) uniform side; (e) uniform + RL apron front; (f) side of uniform + apron](image)

### 3.5.4 Air gap measurement size

Both unclothed and clothed manikins were scanned, then the data processed and imported using FreeCAD software (a parametric 3D CAD modeller). The developers of this software were Jürgen Riegel, Werner Mayer and Yorik van Havre. The two scans were aligned based on various points of nodules that were shifted slightly in points X, Y, Z; see Figure 3-4.
The shifting was paramount in ensuring that the clothed scans perfectly aligned with the unclothed scans. Several cross-sections were then made in various positions, but a constant thickness of 10 cm was maintained around the chest, waist and hip areas. So, we can maintain the average results from the same cross-section. The correlation between air gap and clothing fit was extracted by 3D scanning technology [48]. The average air gap size was obtained by taking the average of three measurements of high value. In the same cross-section, the results represent a high value when there is a greater gap size between the cloth and body (loss) and a lower value when there is less space between the body and cloth (fit), so we have taken a measurement of three for the higher value, the same for the lower value and then take the average. The gap size was measured between the body surface and the clothing surface in mm. The aim of the investigation was mainly to ensure that the design fitted perfectly on the female body.
3.5.5 Thermal comfort testing

3.5.5.1 Sweating thermal manikin

A sweating female thermal manikin (Newton) manufactured by ThermDAC control and software by MTNW were used in this study to replace a human female. The manikin height is 1.70 m and the body surface area is 1.8 ± 0.3 m². The surface of the manikin included 20 independently controlled thermal zones. The manikin measured both the thermal and evaporative resistance of the medical scrub uniform and three types of commercial lead aprons. The skin temperature and power requirement for each zone on the manikin, as well as the surrounding temperature, were recorded with MTNW software. Figure 3-5 shows the zones selected for the experiments.

Both dry and wet tests were performed on each manikin. The dry test took the measurements while the manikin was unclothed. After the manikin was fully dressed, measurements were taken after 45 min. of system stabilisation. After the dry heat loss measurements, the manikin was clothed in undergarments (bra and briefs) and the medical uniform only. The readings from the manikin in undergarments and uniform were the baseline references for the dry and wet tests. The average of three tests was
reported for each set of clothing. The same procedure was applied for the wet test. All
the garments were preconditioned in the same environment for 12 hours in order for
them to reach equilibrium conditions, so that the manikin could stabilise more quickly.
The first test was at 23 °C and 50% RH for the dry test, and the second was at 35 °C and
40% RH for the wet test.

For the wet test, the skin layer of the manikin was purposely wetted before dressing in
order to provide an evaporative surface. The wetting was done by spraying distilled
water onto the manikin's skin layer. In order to keep the manikin moist during the wet
test, the total perspiration rate of the manikin was set to 300 mL/(hr.m²). Measurements
were taken for 45 min. after the manikin was fully dressed. The 45 min. duration was
chosen to allow sufficient time for the manikin within the uniform and apron
combination to reach steady-state conditions and at maximum saturation in moisture
absorption, if there was any.

The female thermal manikin was clothed in underwear made of 100% cotton, a size 14
bra made of nylon and elastane, a size 14 sleeved T-shirt made of 100% cotton, a full
medical scrub shirt and pants uniform, both size L and made of 65% polyester and 35%
cotton, size 14 socks made of cotton and athletic shoes. The aprons, sourced from Puls
Bay Medical Pty Ltd (Medical Radiation Concepts), were placed on top of these
ensembles on the manikin before testing, as shown in Figure 3-6. The lead aprons used
in this study have an outer layer of plain-weave nylon fabric of 12.2 picks per cm and
14.5 ends per cm.
3.5.5.2 Dry thermal resistance \((R_{ct})\) of a garment

The thermal resistance to dry heat transfer test was measured on a heated manikin in a relatively calm environment (there was little air flow), 50% RH and 23 °C. Equation 3.2 [49] was used to calculate thermal resistance:

\[
R_{ct} = (T_{\text{skin}} - T_{\text{amb}}) \div \frac{Q}{A}
\]

Equation 3.2.

where \(R_{ct}\) is the thermal resistance \([\text{m}^2 \cdot \text{°C/W}]\), \(T_{\text{skin}}\) is the zone average temperature \([\text{°C}]\), \(T_{\text{amb}}\) is the ambient temperature \([\text{°C}]\) and \(Q/A\) is the area weighted heat flux \([\text{W/m}^2]\).

The intrinsic clothing insulation \((R_{cl})\) is defined as the insulation from the skin surface to the clothing surface, which can be determined via \(R_{ct}\) value using Equation 3.3 [49]:

\[
R_{cl} = R_{ct} - \left(\frac{R_c}{f_{cl}}\right)
\]

Equation 3.3.
where $R_{cl}$ is the intrinsic clothing insulation $[m^2 \cdot ^\circ C/W]$, $R_a$ is the thermal insulation of the unclothed manikin $[m^2 \cdot ^\circ C/W]$ and $f_{cl}$ is the clothing area factor, which was estimated according to [50].

### 3.5.5.3 Evaporative resistance ($R_{et}$)

The evaporative resistance of clothing describes the resistance to evaporative heat transfer from a heated sweating manikin in a 35 °C and 40% RH and relatively calm (i.e. little air flow) environment. Equation 3.4 was used to calculate evaporative resistance [51]:

$$R_{et} = \frac{(P_{sat} - P_{amb})}{Q/A} - \frac{(T_{skin} - T_{amb})}{R_{ct}}$$

Equation 3.4.

where $R_{et}$ is the evaporative resistance $[m^2 \cdot Pa/W]$, $P_{sat}$ is the saturation vapour pressure at skin temperature $[Pa]$, $P_{amb}$ is the vapour pressure at ambient temperature $[Pa]$, $Q/A$ is the area weighted heat flux $[W/m^2]$, $R_{ct}$ is the thermal resistance $[m^2 \cdot ^\circ C/W]$, $T_{skin}$ is the zone average temperature $[^\circ C]$ and $T_{amb}$ is the ambient temperature $[^\circ C]$. $\frac{(T_{skin} - T_{amb})}{R_{ct}}$ = dry heat loss $[W/m2]$. $P_{sat} = 13303\cdot10^{8.10765 - (1750.29/(235 + T_{skin}))}$. $P_{amb} = RH \cdot 133.3 \cdot 10^{8.10765 - (1750.29/(235+T_{amb}))}$.

The intrinsic evaporative resistance ($R_{ecl}$) of the clothing ensemble can be calculated using Equation 3.5:

$$R_{ecl} = R_{et} - (R_{ea}/f_{cl})$$

Equation 3.5.

where $R_{ecl}$ is evaporative resistance $[m^2 \cdot Pa/W]$, $R_{ea}$ is the evaporative unclothed resistance $[m^2 \cdot Pa/W]$ and $f_{cl}$ is the clothing area factor, which was estimated according to [50].

### 3.5.6 Moisture management

A Moisture Management Tester (MMT) measures the liquid management properties of fabrics according to AATCC TM 195:2009 [52], liquid moisture management properties of textile fabrics. Five fabric specimens measuring 80 mm × 80 mm were measured and the liquid moisture transport behaviour in different directions of the sample was assessed. The following grading was used for the evaluation; see Table 3-6.
Table 3-6 Grading table of MMT indices [52]

<table>
<thead>
<tr>
<th>Index</th>
<th>Grade</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetting time (sec)</td>
<td>Top</td>
<td>≥ 120</td>
<td>20–119</td>
<td>5–19</td>
<td>3–5</td>
<td>&lt; 3</td>
</tr>
<tr>
<td></td>
<td>No wetting</td>
<td>Slow</td>
<td>Medium</td>
<td>Fast</td>
<td>Very fast</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>≥ 120</td>
<td>20–119</td>
<td>5–19</td>
<td>3–5</td>
<td>&lt; 3</td>
</tr>
<tr>
<td></td>
<td>No wetting</td>
<td>Slow</td>
<td>Medium</td>
<td>Fast</td>
<td>Very fast</td>
<td></td>
</tr>
<tr>
<td>Absorption rate (%/sec)</td>
<td>Top</td>
<td>0–10</td>
<td>10–30</td>
<td>30–50</td>
<td>50–100</td>
<td>&gt; 100</td>
</tr>
<tr>
<td></td>
<td>Very slow</td>
<td>Slow</td>
<td>Medium</td>
<td>Fast</td>
<td>Very fast</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>0–10</td>
<td>10–30</td>
<td>30–50</td>
<td>50–100</td>
<td>&gt; 100</td>
</tr>
<tr>
<td></td>
<td>Very slow</td>
<td>Slow</td>
<td>Medium</td>
<td>Fast</td>
<td>Very fast</td>
<td></td>
</tr>
<tr>
<td>Max wetted radius (mm)</td>
<td>Top</td>
<td>0–7</td>
<td>7–12</td>
<td>12–17</td>
<td>17–22</td>
<td>&gt; 22</td>
</tr>
<tr>
<td></td>
<td>No wetting</td>
<td>Small</td>
<td>Medium</td>
<td>Large</td>
<td>Very large</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>0–7</td>
<td>7–12</td>
<td>12–17</td>
<td>17–22</td>
<td>&gt; 22</td>
</tr>
<tr>
<td></td>
<td>No wetting</td>
<td>Small</td>
<td>Medium</td>
<td>Large</td>
<td>Very large</td>
<td></td>
</tr>
<tr>
<td>Spreading speed (mm/sec)</td>
<td>Top</td>
<td>0–1</td>
<td>1–2</td>
<td>2–3</td>
<td>3–4</td>
<td>&gt; 4</td>
</tr>
<tr>
<td></td>
<td>Very slow</td>
<td>Slow</td>
<td>Medium</td>
<td>Fast</td>
<td>Very fast</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>0–1</td>
<td>1–2</td>
<td>2–3</td>
<td>3–4</td>
<td>&gt; 4</td>
</tr>
<tr>
<td></td>
<td>Very slow</td>
<td>Slow</td>
<td>Medium</td>
<td>Fast</td>
<td>Very fast</td>
<td></td>
</tr>
<tr>
<td>One-way transport capacity (OWTC)</td>
<td>&lt; –50</td>
<td>Poor</td>
<td>–50 to 100</td>
<td>100 to 200</td>
<td>200 to 400</td>
<td>&gt; 400 Excellent</td>
</tr>
<tr>
<td>Overall moisture management capability (OMMC)</td>
<td>0–0.2</td>
<td>Poor</td>
<td>0.2–0.4</td>
<td>0.4–0.6</td>
<td>0.6–0.8</td>
<td>&gt; 0.8 Excellent</td>
</tr>
</tbody>
</table>

The accumulative one-way transport capability (OWTC) represents the difference in the accumulative moisture content between the two surfaces of the fabric, and determines to a large extent whether the fabric has good moisture management properties. In terms of comfort, the higher the OWTC, the more quickly and easily liquid sweat can be transferred from the skin to the outer surface of the fabric, thus keeping the skin dry.

The overall moisture management capability (OMMC) indicates the overall capability of the fabric to manage the transport of liquid moisture. The larger value of the OMMC, the higher the overall moisture management capability of the fabric.

### 3.5.7 Air permeability

Air permeability was measured using the air permeability tester MO21S by SDL Atlat. The experiment was based on EN ISO 9237.1995 [53]. According to the standard, air permeability is measured as the flow of air per unit area of fabric. The air permeability was calculated by dividing the mean airflow by the test area of the fabric specimen. The
fabric sample size was 80 mm × 80 mm and five measurements were taken. It is expressed in millimetres per sec. and is calculated using Equation 3.6:

\[ R = \frac{q v}{A} \times 167 \]  
Equation 3.6.

Where:

\( q v \) is the arithmetic mean flow-rate of air.

\( A \) is the area of fabric under test in square centimetres; \( A = 4.908 \text{ cm}^2 \).

\( 167 \) is the conversion factor from cubic decimetres.

3.5.8 Sensory comfort

3.5.8.1 Pressure distribution on apron and design

The pressure generated by the aprons was measured using Innovative Pressure Mapping Solutions from Vista Medical Ltd. At first, the female manikin in a standing position with a full medical scrub uniform was measured. Then the pressure mat was placed strategically on a shoulder in a horizontal manner, with care taken to avoid folding or kinking to eliminate discrepancies in the measurements. Sticky tape was used to secure the mat on shoulder, under arm and chest so that the mat did not move when the apron was put on. The average of triplicate tests was reported for each apron. A similar systemic procedure to measure the air gaps was applied with the pressure distribution methods. The advanced software made the measurements and data with graphic designs easy to extract from the computer (see Appendix 1).

3.5.8.2 Stiffness of cloth

The standard test method for measuring the stiffness of clothing (AS 2001.2.9) was used [54]. The stiffness of sheets for lead aprons was measured using a 133 Shirley stiffness tester. A rectangular strip (25 mm wide × 250 mm long), supported on a horizontal platform, was clamped at one end and the strip then allowed to overhang and bend under its own weight.

The flexural rigidity \( G \), in micronewton-metres, was calculated separately for lengthwise and widthwise directions using Equation 3.7:
Equation 3.7.

\[ G = 9.8 \, mC^3 \times 10^{-6} (\mu N m) \]

where \( C \) is the bending length and \( m \) is the mass per unit area of the sample in grams per square metre (g/m²).

The bending modulus (\( q \)), in micronewtons per square metre, was calculated separately for lengthwise and widthwise directions using Equation 3.8:

\[ q = \frac{12G \times 10^3}{t^3} (\mu N \, m^2) \]

where \( G \) is the flexural rigidity and \( t \) is the sample thickness in mm.

### 3.5.8.3 Stretch and recovery

The BS EN 14704-1:2005 [55] test method was used for calculating the stretch and recovery properties of the experimental samples in wale and course directions using an Instron 5565A instrument. The size of each specimen was a rectangular strip 50 mm wide \( \times \) 750 mm long. The two clamps were set properly aligned and parallel, and the gauge length was 75 mm \( \pm \) 0.5 mm (\( L_1 \)). The extension and retraction rate of the specimen was set at 50 mm/min. The fabric specimen was stretched by cycling five times from 0 N to 30 N load, and the 30 N load was maintained for 5 sec.; the extension (cross-head movement) at 30 N was recorded as \( L_2 \). The sample was then removed from the clamps and allowed to relax on a flat, smooth surface and its length was remeasured after 1 min. as \( L_3 \). The stretch and recovery results were then calculated using Equation 3.9 and Equation 3.10 [56]. The arithmetic mean of five cycles was taken to determine the stretch and recovery properties of the samples.

Extension %, \( E = 100(L_2 - L_1)/L_1 \)  

Equation 3.9.

Residual extension after 1 min, \( R_1 = 100(L_3 - L_1)/L_1 \)  

Equation 3.10.
3.5.9 X-ray shielding measurement performance

3.5.9.1 X-ray exposure testing (method one)

All X-ray data was collected at the Medical School laboratory at RMIT. Samples were tested for X-ray attenuation using a medical X-ray machine (SHIMADZU X-ray system). As shown in Figure 3-7, the distance from the X-ray beam source to the fabric (SID, the ‘source to image distance’ used in radiography, denoting the distance from the X-ray source to the centre of the fabric) was 80 cm. Samples were exposed to X-rays at tube voltage 80 kVp, and tube current and time for 12 milliampere-seconds (mAs). The shielding ability of each sample was evaluated by comparing their transmission doses with the measured transmittance doses for reference lead samples. A Rad-Check Plus dosimeter was used to measure transmittance. Five different positions, four different corners and the centre, on each sample were exposed independently and the mean value for each sample was calculated. The fabric sample size was 15 cm × 15 cm.

The same procedure was also adopted for the lead samples and fabrics without any coating in order to compare shielding ability among the samples.
3.5.9.2   X-ray exposure testing (method two)

Two exposure experiments were conducted on the samples before and also after the abrasion and stretch tests. Samples were tested for X-ray attenuation using a medical X-ray machine (Shimadzu) as shown in Figure 3-8. The distance from the X-ray beam source to the fabric was 80 cm (SID); the radiation detector was placed just below the fabric. Samples were exposed to X-rays at tube voltage 80 kVp and tube current with a time measuring for 12 milliampere-seconds (mAs). The shielding ability of each sample was then evaluated by comparing the transmittance doses with the measured...
transmittance doses for reference lead samples. RaySafe detection was used to measure transmittance and absorption.

Five different exposures of each sample were exposed independently and the mean value for each sample was calculated. The fabric sample size was 10 cm × 10 cm. The same procedure was also adopted for the lead samples and fabrics without any coating in order to compare shielding ability among the samples. The unit of measurement used was milligray (mGy) for dose transmitted or absorbed, and the dose rate unit of measurement was milligray per second (mGy/s). Both methods were performed at the RMIT Medical School laboratory in one of the X-ray suites.

![Figure 3-8 Gallery of X-ray exposure experiment](image)

### 3.5.10 Statistical data analysis

The statistical analyses were performed using Microsoft Excel 2016. Descriptive statistics including frequencies, means and standard deviations were used in reporting the final results, including detailed perceptions of and requirements for the coated samples, such as shielding performance.
Chapter 4: Shielding and Comfort Performance of Selected Casing Fabrics for Use in X-Ray Protective Aprons

4.1 Introduction

Ionising radiation in human health is primarily used to kill cancerous cells and to diagnose disease and injury [3]. X-rays are the most common form of radiation used in medical diagnosis. The radiation is passed from a source through a specific part of the patient’s body to generate images (radiography). During such procedures, the resulting ions affect normal biological processes and ecological balance [57]. To prevent unnecessary exposure of the radiologist and the patient, various protective measures have been used which are standardised and being constantly improved [3].

Lead aprons are the most common type of personal shielding in radiological departments and the medical imaging industry. Lead is an ideal material for radiation protection, but it compromises on the comfort of the wearer [58]. The issue of comfort becomes even more prominent when worn for long durations. According to Van et al. [59], the most common comfort issue when selecting a lead apron is the weight of the apparel. Lead is a heavy metal. The prolonged use of heavy aprons and other apparel can lead to discomfort, constant back pain and the risk of permanent back problems. Modern technology has resulted in ultra-lite and lightweight aprons, but most of them are still heavy, about 3.8 kg [60].

Clothing insulation has a significant impact on thermal comfort, because it influences heat loss and consequently thermal balance. Multi-layered insulation clothing can prevent heat loss or lead to overheating. Medical protective clothing should not induce any thermal discomfort. Such discomfort experienced by surgeons can decrease their psychomotor skills and adversely influence the way an operation procedure is carried out [61].

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1 The outcomes of this chapter have been published in the TBIS-APCC 2016 conference proceedings and Journal of Fiber Bioengineering and Informatics (JFBI).
This chapter investigates the comfort performance of a specific range of textile fabrics that could be used as alternative casing for protective aprons. In ascertaining the comfort elements in the current line of aprons, the purpose of this research is also to provide a basis for proposing alternative enhancements to the fabric finishing, technology and/or material used. These proposed alternatives should fulfil a balance between radiation protection and thermal comfort.

4.2 Experimental

The material specifications are illustrated in Table 4-1. Two lead-equivalent samples were used as the benchmark for comparison. A regular lead-equivalency sheet, RL, made from rubber, polyvinyl chloride (PVC) and lead powder, weighing 2.4 kg/m², was used as the inner layer for the experiments. Similarly, a Lite Lead sheet, LL, also made from rubber, PVC and lead powder was used and weighed 2.1 kg/m². Both samples were obtained from Medical Concepts Australia Pty Ltd.

Table 4-1 Material properties

<table>
<thead>
<tr>
<th>Material code</th>
<th>Material composition</th>
<th>Construction</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No. of Ends/cm</td>
<td>No. of Wales/cm</td>
</tr>
<tr>
<td>RL</td>
<td>Regular lead</td>
<td>Sheet (inner layer)</td>
<td>-</td>
</tr>
<tr>
<td>LL</td>
<td>Lite Lead</td>
<td>Sheet (inner layer)</td>
<td>-</td>
</tr>
<tr>
<td>N</td>
<td>100% nylon</td>
<td>Plain woven (outer layer)</td>
<td>14.5</td>
</tr>
<tr>
<td>NW</td>
<td>Nylon/wool</td>
<td>Weft knitting single jersey (outer layer)</td>
<td>-</td>
</tr>
<tr>
<td>P</td>
<td>100% polyester</td>
<td>Plain woven (outer layer)</td>
<td>7.4</td>
</tr>
<tr>
<td>PC</td>
<td>50% cotton, 24% modal, 24% bamboo, 2% polyester</td>
<td>Weft knitting double jersey (outer layer)</td>
<td>-</td>
</tr>
<tr>
<td>K</td>
<td>100% Kevlar</td>
<td>Plain woven (outer layer)</td>
<td>8.6</td>
</tr>
<tr>
<td>KW</td>
<td>Kevlar/wool</td>
<td>Weft knitting single jersey (outer layer)</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 4-1 shows the plain-weave structure of the woven fabrics made from nylon (N), polyester (P) and Kevlar (K). Nylon and polyester are commonly used as casing materials for commercial lead aprons because of their strength, resilience, light weight and durability. Kevlar, which is much stronger than nylon and polyester, was used as
another casing material. Figure 4-2 shows the weft-knitted fabric structure used as a comparison in this research, including plated nylon/wool (NW) [62], knitted multi-fibre blend (PC) and Kevlar/wool (KW) fabrics.

The methods that were used in the experiments are described in Chapter 3:
- X-ray measurement
- Scanning electron microscopy (SEM)
- Material thickness
- Mass per unit area
- Air permeability
- Moisture management

**4.3 Results and Discussion**

**4.3.1 X-ray measurements**

The initial X-ray exposure was measured without any fabric and was documented as a control. Fabrics and lead sheets were measured for X-ray shielding at a medium level of radiation, 80 kVp. The results are shown in Figure 4-3 and Figure 4-4. The value of the transmittance corresponds with the proportion of X-rays that penetrated through the specimen. It indicates the shielding effectiveness of the samples tested. A higher transmittance value corresponds to a lower X-ray absorption, meaning that the sample is less effective for radiation protection.
Figure 4-3 shows that the transmittance values for RL and LL were 16% and 18%, respectively, which indicates that these fabrics can absorb most of the X-ray radiation. The other fabric samples transmitted almost all the X-rays and therefore cannot be considered as having any radiation-shielding effect. Since the nylon or polyester casing fabrics have no radiation-shielding effects, despite their structures being very tight as observed from the SEM images, the primary purpose of using these casing fabrics is to contain X-ray shielding sheets or facilitate coating as a fabric substrate for X-ray protection [63]. Hence, the casing materials should be light for apron weight reduction. Very lightweight fabrics are not considered physically effective radiation shields, but would ideally offer the highest possible protection if coated with a suitable radiation absorber.
Figure 4-4 represents the same samples after abrasion (40,000 cycles). It can be seen that there is no significant change in the shielding efficiency of the lead materials. RL and LL showed the same attenuation to X-ray by 16.3 and 18%, respectively. That means the lead material represents durability against abrasion. This is due to the PVC and the industrial process. It is clear that the abraded fabric samples have no effect on X-ray protection, as indicated by nearly 100% transmittance. Rubbing or abrasion nonetheless affected the fabric durability.

4.3.2 Fabric physical properties

![Mass and thickness properties](image)

Figure 4-5 Mass per unit area and thickness of experimental materials

Figure 4-5 shows the differences of the proposed fabrics in thickness and weight. The RL and LL have heavier weights of 2600 g/m² and 2200 g/m², respectively, because they are made from lead powder. On the other hand, the KW and NW weigh 520 g/m² and 462 g/m², respectively, indicating that they are as heavy as the casing material. Samples PC, K and P are medium to lightweight fabrics. Physical properties are considered a significant comfort parameter for fabric in industrial garments. Figure 4-5 reveals that the heaviest samples are the lead samples (due to the lead particles and PVC), and then nylon or polyester. The second heaviest category is the knitted fabrics, KW, NW and PC. The lightweight samples are N 162 g/m² and P 154 g/m². Thickness typically plays an important role in X-ray transmittance; however, the main contribution comes from the high atomic number and the density and cross-section of the atomic number. The
benchmarks LL and RL have medium thickness compared to the knitted fabric samples. It is, however, worth noting that the lead samples may comprise a couple of sheets and must be encased with a fabric material. On the other hand, the knitted plated wool fabric has a nylon-faced side, which could be coated with X-ray absorbers, and the side next to the skin would have wool for enhanced comfort.

Fabric thickness affects the comfort properties of garments. It also determines the effectiveness of X-ray protection. Thickness tends to be related to fabric density. Figure 4-5 show that samples N, P and K are in the medium-to-low thickness range. So they have relatively desirable comfort characteristics (medium thickness), while all the other samples are in the upper thickness range. In this context, the knitting samples NW and KW are the thickest (1.25 mm and 1.15 mm) among the samples, and are thicker than the lead sheets. So, they are likely to have the least desirable comfort characteristics because of their thickness. Hence, these fabrics are not considered as the casing material.

4.3.3 Abrasion resistance

Abrasion is defined as the wearing away of any part of the fabric through rubbing against another surface. With use, fabrics are subjected to abrasion and this may result in wear, deterioration, damage and loss of performance. However, abrasion resistance is only one of several factors contributing to wear performance or durability [56]. Figure 4-6 indicates that the RL and LL samples showed less than 1% mass loss after 40 000 rubs. This can be explained by the material type – PVC lead sheeting with a smooth surface. The woven group of N and P showed the next lowest mass loss (3%). Sample P showed a change in colour – becoming a lighter shade than the original fabric colour – after 20 000 rubs. The mass loss after 40 000 rubs can be attributed to the water-repellent coating on the commercial lead casing. Surprisingly, the woven sample K displayed a high average mass loss (70%) after almost 25 000 rubs. The colour appearance of K started to fade after 15 000 rubs and this indicates that the woven K fabric is less durable than N and P.
Figure 4-6 shows that the knitted group had fluctuating results in the average of mass loss. For example, the PC sample represents the highest mass loss, with almost 80% after a much lower number of rubs of 20,000. This means that fabric PC has less durability in relation to rubbing due to cotton being shorter and weaker than other fibres evaluated. The use of single thread of yarns also leads to have the lowest weight of 228 g/m² and the lowest thickness (0.81 mm) among the knitted group. KW had a 40% mass loss after 28,000 rubs and there was a change in its colour appearance at 20,000 rubs. The NW sample showed more resistance to rubbing and showed a mass loss of 15% only after 40,000 rubs.

In Table 4-2, images of the samples under magnification show how each sample was affected by the number of rubbing cycles. Some samples showed no change on the surface, while others showed the breakdown of the yarns. Three samples deteriorated completely (PC, K and KW). Samples P, N and NM showed more resistance on the
surface, with marginal colour fading. The lead benchmarks revealed high resistance to abrasion and showed no significant change to the surface, due to their material components – PVC and lead powder.
Table 4-2 Optical images of samples appearance under magnification before and after applying the abrasion test

<table>
<thead>
<tr>
<th>Samples before abrasion test</th>
<th>Samples after abrasion test</th>
</tr>
</thead>
<tbody>
<tr>
<td>RL</td>
<td></td>
</tr>
<tr>
<td>LL</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td></td>
</tr>
<tr>
<td>NW</td>
<td></td>
</tr>
</tbody>
</table>
4.3.4 Air permeability

Air permeability, otherwise referred to as breathability, is the ability of a fabric to allow air or moisture vapour to move through it. The air permeability of a fabric can influence the wearer's comfort in several ways. Firstly, a material that is permeable to air is also, in general, likely to be permeable to water, in either the vapour or the liquid phase. Thus, both the moisture-vapour permeability and the liquid-moisture transmission are normally closely related to air permeability. Secondly, the thermal resistance of a fabric is dependent on the enclosed still air and this factor, in turn, is influenced by the fabric structure and air permeability [64].

Figure 4-7 shows the air permeability test results. The properties of the lead samples LL and RL showed zero air permeability. It is therefore understandable that these samples cannot leak radiation transmittance. Air permeability, however, is not a good feature for X-ray protection but is a necessary attribute for comfort. The air permeability results indicate that the PC knitted fabric had the highest breathability attributes among all the samples, with 71.3 mm/s. The K woven fabric had the lowest air permeability of 6.5 mm/s, followed by the N sample with 9.5 mm/s. Finally, the KW, NW and P fabrics all achieved reasonable air permeability. The woven P sample had lower air breathability than the knitted samples KW (30.6 mm/s) and NW (39.7 mm/s). Table 4-1 and Table 4-2 show that, even though KW contained a similar amount of nylon yarn as NW, the addition of wool yarn made the fabric thicker and created voids between yarns which allowed air to easily pass through. This observation supports the view that air permeability depends on the physical properties of fabrics, such as construction, mass, thickness and yarn count.
The reasonable permeability of the three knitted fabric samples PC, NW and KW might be due to the open structure of the knit. Figure 4-7 shows that the woven samples N, P and K had lower permeability compared to the knitted samples due to their different fibre properties. This may be because of the weave structure, plus the water-repellent coating on samples P and N for casing the apron.

4.3.4.1  Fabric moisture management

An individual wearing RL or LL will experience a clammy or damp sensation because of the non-existent moisture management. Such lead sheets are uncomfortable to wear for any amount of time, even in a well-ventilated room. However, most facilities that utilise radiation tend to prioritise safety over ventilation.

Table 4-3 shows the moisture management results for all moisture management property indexes. Overall moisture management capacity (OMMC) is an index that determines the overall ability of a fabric to handle liquid moisture transport. This includes three performance aspects: one-way liquid transportability, moisture drying speed (bottom side maximum spreading speed) and moisture absorption rate. The larger the OMMC value, the higher the moisture management ability of the fabric.

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Top surface</th>
<th>Bottom surface</th>
<th>Accumulative one-way transport [%]</th>
<th>OMMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>RL</td>
<td>3.9</td>
<td>32.6</td>
<td>5</td>
<td>1.2</td>
</tr>
<tr>
<td>LL</td>
<td>9.4</td>
<td>40.6</td>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>N</td>
<td>4.8</td>
<td>61.8</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>NW</td>
<td>8.7</td>
<td>31.0</td>
<td>14</td>
<td>1.8</td>
</tr>
<tr>
<td>P</td>
<td>5.2</td>
<td>55.2</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>PC</td>
<td>4.1</td>
<td>41.0</td>
<td>20</td>
<td>2.6</td>
</tr>
<tr>
<td>K</td>
<td>4.7</td>
<td>51.7</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>KW</td>
<td>6.0</td>
<td>90.0</td>
<td>10</td>
<td>1.6</td>
</tr>
</tbody>
</table>
The zero OMMC values for samples RL, LL, N, P and K indicate that these samples had very poor overall moisture management ability. Radiation shielding that uses naturally dense materials such as pure lead sheets or heavy fabrics certainly compromises thermal comfort. The NW and PC fabrics showed poor OMMC; however, the KW fabric showed a relatively high OMMC (0.7, very good). Nevertheless, it is essential that there is an emphasis on radiation shielding before comfort characteristics. The RL and LL samples could be considered waterproof due to their very slow water absorption and spreading rate on the inner surface of the fabric, as well as zero penetration and poor one-way liquid moisture transport. The structure of RL and LL is flat sheeting without any weave structure.

Figure 4-8 shows the fabric maximum wetting radii with moisture absorption and spreading rate. The woven fabric samples N, P and K all had poor liquid moisture management properties, with very slow water spreading rates and no wetted areas on their bottom surfaces. These fabrics also had negative or insignificant one-way transport capacities, indicating that sweat cannot diffuse easily through these fabrics. The sweat on the surface next to the skin will therefore accumulate on top of the surface and result in discomfort for the wearer. On the other hand, the knitted fabric samples NW, PC and KW had medium-to-fast liquid absorption, penetration and spreading rates on their bottom surfaces. This is due to their blended wool/cotton composition (see Table 4-1).

As shown in Table 4-3 and Figure 4-8, the KW sample had the highest absorption rate on the top surface (next to the skin) with 90%, while NW had an absorption rate of 31% on the top surface. A higher absorption rate is related to better comfort characteristics, especially subjective perceptions of the sweat sensation. The K fabric had zero penetration and thus no one-way transport, slow spreading and very slow absorption. The characteristic result of most of the samples being slow spreading with no OMMC indicates that the wearer is likely to experience clamminess, i.e. moisture remaining either on the next-to-skin surface or within the fabric. This supports findings from Mahbub [65] about thermal comfort for a similar type of fabric.
Fabric sample N is a very slow absorbing and drying fabric which was characterised as having poor one-way transport. It had very slow spreading speed without absorption of moisture, indicating that moisture cannot easily diffuse across the fabric and evaporate into the environment. NW showed a high absorption rate on the wool surface and this suggests that wool can absorb water faster than nylon. Hence, having the wool face next to the skin is better for moisture management. Furthermore, though the wet-out radius for the top surface was smaller than for the bottom surface (Table 4-3), the top surface still had moderate ability to transfer the absorbed water to the outer surface. Figure 4-8 also shows that the wet-out radius is different between the two surfaces for NW. The NW fabric had a relatively large spreading rate (3.1 mm/s) and large wet-out radius (18 mm) on the bottom, which indicates that liquid moisture can spread quickly, transfer easily and dry quickly on the outer surface of this fabric. The fabric’s accumulative one-
way transport capacity (OWTC) was 145.8% and the OMMC was 0.4. These OMMC and OWTC values are good, and this suggests that the NW knitted fabric had a moderate water penetration rate between both surfaces. Generally, samples N, P and K showed poor results for moisture management properties.

4.4 Conclusion

This chapter has evaluated the effectiveness of X-ray aprons to determine their protectiveness and comfort performance. The lead apron material is uncomfortable to wear because of its heavy weight, non-permeability to air, and inability to absorb and allow for the evaporation of moisture in the form of sweat. Six fabrics and two commercial lead sheets have been tested and evaluated. The lead sheets had very poor comfort characteristics but excellent radiation-shielding ability. On the other hand, the knitted fabric samples NW, PC and KW showed poor absorption of X-ray radiation and therefore did not have any effective shielding ability. The abrasion resistance of the samples in the study varied due to the weave structure and the end use of each sample. For instance, sample NW had the highest resistance to abrasion, which means it was more durable than KW and PC.

In terms of comfort characteristics, the air permeability of all samples varied. LL and RL showed an expected zero mm/s liquid moisture spreading rate on their bottom surfaces due to their zero air permeability. In general, the highest results for air permeability were indicated by samples PC, P, NW and KW. These samples showed good comfort properties, particularly in terms of moisture management. These fabrics could be used for apron casing to replace the woven fabrics, which had poor comfort performance. The woven fabrics also showed ineffectiveness for radiation shielding. However, all fabrics showed enhanced comfort properties compared with lead sheets.

Further research is suggested using knitted plated wool fabric as a base material and coating it with an X-ray absorber material on the front side. This would save half the weight of casing material for an apron.
Chapter 5: Comfort Evaluation of Selected Commercial Lead Aprons used in Diagnostic Imaging

5.1 Introduction

Currently, the material mostly used in commercial lead aprons is lead oxide mixed with either synthetic rubber or PVC and elastomer resin to make sheets which can be cut and sewn into various shapes. The use of textile fabrics (woven fabrics) is as a casing material only, to hold the sheets [5]. Recently, a new approach of using textiles as casing materials to hold the shielding materials has been reported [63]. The importance of choosing the right materials for protective clothing is to ensure wearers can maintain thermal comfort, because clothing affects the body’s heat exchange. Additionally, clothing has an influence on metabolic rate, which also affects thermal comfort [66]. It has been reported that humans have different metabolic rates that can fluctuate due to activity levels and environmental circumstances [66, 67].

There are a limited number of reports on thermal comfort dealing with radiation protective clothing or personal protective clothing (PPC). Lead aprons as PPC need to be evaluated from a thermal comfort point of view. In some cases, the operation of an X-ray procedure may take more than one hour, which may cause thermal stress to the radiographer who wears this type of apron due to the heavy weight of the apron – ranging from 3.4 kg to 4 kg – and the impermeability of the material used [68]. Strong evidence in two important studies has found that radiographers wearing lead aprons indicated an uncomfortably warm sensation, due to the higher clothing insulation value of the apron (+1.25) according to the ISO 7730 Standard used for their study design [69, 70]. Hence, the radiographer wearing a lead apron does not achieve a balanced thermal comfort at an air temperature of 19 °C, even at a high air velocity (v = 1 m/s) [69]. The concept of thermal comfort is closely related to thermal stress. Generally, humans do not perform well under thermal stress [37, 71].

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2 The outcomes of this chapter have been submitted for publication in the Journal of the Textile Institute (JOTI) 2017. See p.12.
Another comfort issue associated with lead aprons is their heavy weight. Prolonged wear of heavy lead aprons can impact the health, while reduced mobility and walking of wearers is also seen due to garment stiffness, bulk and fit. It has been found by Ross et al. [35] that interventional cardiologists reported more skeletal problems, back and neck pains than rheumatologists and orthopaedic surgeons, complications which were linked to the cardiologists wearing lead aprons for protection. The location of high discomfort was reported as being in the neck/shoulder region rather than in the lower back when wearing a lead apron. The higher rate of discomfort reported by the cardiologists may be due to greater pressure generated within the spinal discs while supporting the weight (8 kg) of a one-piece suit directly through the shoulder girdle. Such physiological pressures are frequently associated with a decreased work capacity and an increased metabolic rate [72, 73]. Long-term compressive loading can lead to micro-trauma in spinal structures, in addition to altered metabolism. Similarly, other studies have outlined the significant effect of the weight load, particularly on the back and shoulder regions [32, 36]. Another study has confirmed that all PPC garments showed an increase in metabolic rate compared to the control condition. The highest recorded increase in metabolic rate (18.7%) was seen in the workwear (2 layer) (A) garment. All suits showing an increase in metabolic rate of 10% or more over the control proved to be significant (p<0.05) [74].

The purpose of the current chapter is to investigate and evaluate three commercial lead aprons for comfort using different objective and subjective measurements. A thermal manikin has been used to evaluate the thermo-physiological comfort in terms of thermal and vapour resistance, fit in terms of the air gap size, and the stiffness of the aprons, as well as the effects of weight distribution. The findings are intended to help address the engineering challenges in the area of design and construction of protective garment systems and garment structure to accomplish the best balance between the physiological obligations required by the systems and the protection offered by them. There are limitations to this pilot study which is that it is hard to make a fair comparison with previous references due to variation in testing conditions and limited data available.
5.2 Materials and Experiments

Apparatus used in this study have been described in Chapter 3. The material properties are shown in Table 5-1. Three different commercial aprons were used as benchmarks for evaluation plus the normal medical scrub uniform worn in hospitals. Also, Table 5-1 shows the measurements for each garment used in this experiment. Each apron and uniform was measured individually and then the mean value of the weight and thickness was measured based on the order of the layers.

Table 5-1 Physical properties of experimental uniform and aprons

<table>
<thead>
<tr>
<th>Experimental garment configuration</th>
<th>Mean weight (kg)</th>
<th>Size</th>
<th>Functional layer</th>
<th>Mean mass/unit area (g/m²)</th>
<th>Mean thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medical scrub uniform (long sleeved cotton shirt + medical scrub shirt + pant uniform)</td>
<td>0.16 0.25 0.37±0.5</td>
<td>L</td>
<td>One inner layer Two outer layers (shirt + pant)</td>
<td>170 202 × 2 ±0.4</td>
<td>0.80 0.40 × 2 ±0.4</td>
</tr>
<tr>
<td>Regular lead tie apron (RL)</td>
<td>3.67±0.1</td>
<td>M</td>
<td>Outer layer nylon Two inner layers of lead sheets Outer layer nylon</td>
<td>122.6 3581.4 × 2 122.6 ±0.5</td>
<td>0.182 0.688 × 2 0.182 ±0.4</td>
</tr>
<tr>
<td>Ultra-Lite tie apron (UL)</td>
<td>3.25±0.5</td>
<td>M</td>
<td>Outer layer nylon Two inner layers of lead sheets Outer layer nylon Layered structure</td>
<td>122.6 3120.8 × 2 122.6 ±0.5</td>
<td>0.182 0.716 × 2 0.182 ±0.5</td>
</tr>
<tr>
<td>Earth-Lite tie apron (EL)</td>
<td>3.04±0.8</td>
<td>M</td>
<td>Outer layer nylon Four inner layers of lead sheets Outer layer nylon Layered structure</td>
<td>122.6 1465 × 4 122.6 ±0.5</td>
<td>0.182 0.516 × 4 0.182 ±0.5</td>
</tr>
</tbody>
</table>

The methods that were used in the experiments are described in Chapter 3:

- Dry thermal resistance ($R_{ct}$)
- Evaporative resistance ($R_{et}$)
- Mass per unit area and material thickness
- Stiffness of lead aprons
- 3D body scanning and air gap measurement
- Pressure distribution for lead aprons
5.3 Results and Discussion

Nylon and polyester have very poor moisture management capacities and are unable to absorb or allow the evaporation of moisture in the form of sweat. The use of knitted fabric plated with wool would improve the comfort performance of the casing material and could be used as a fabric substrate to hold the shielding materials [62],[75].

5.3.1 Thermal resistance of body region

From Figure 5-1 it can be observed that the highest $R_{ct}$ is in the hip zone, followed by the stomach and back regions. This is because the clothing system has three layers or more in those areas. The hip zone was covered by briefs, scrub pants, a cotton long-sleeved shirt, the scrub shirt and the apron. The highest thermal resistance was recorded in the hip region as $0.76 \text{m}^2\cdot\text{°C}/\text{W}$ for EL, followed by $0.74 \text{m}^2\cdot\text{°C}/\text{W}$ for UL and $0.72 \text{m}^2\cdot\text{°C}/\text{W}$ for RL. The $R_{ct}$ of the clothing system in the stomach zone shows the same trend as that of the hip zone but the values are relatively lower, as shown in Figure 5-1. This trend of lower values might be due to the open spaces on each side of the apron; see Figure 3-6. The clothing system would have very poor thermal transfer capacity in these areas, causing discomfort for the wearer in intensive sweating conditions. It is thus important to reconsider the design of the clothing structure to reduce the $R_{ct}$.

Heat transfer is both perceptible (convection, conduction and radiation) and latent (evaporation), and the insulation provided by a clothing ensemble is dependent on the designs and materials used in the garments, the amount of body surface area covered by clothing, the distribution of the fabric layers over the body, the looseness or tightness of fit, and the increased surface area for heat loss[62],[76]. In this experiment, the aprons cover a large surface area of the body and impermeable sheets are used in the aprons, resulting in the prevention of heat loss passing through the clothing system and higher $R_{ct}$ and $R_{ct}$. The high thermal resistance in the hip and stomach areas indicates a higher possibility of heat stress for the wearer. Hence, in some cardiac catheterisation surgery, a radiologist may suffer heat stress when working long hours in the operating theatre. Heat stress usually occurs when the body’s means of controlling its internal temperature starts to fail. Air temperature and factors such as work rate, humidity and clothing worn while working may lead to heat stress.
A lower value of $R_{ct}$, less than 0.37 m$^2$.°C/W, has been observed at the shoulder, chest and thigh regions, indicating that those specific regions have a lower thermal resistance. This means that the clothing has some sort of heat loss or transfer. The reason for the heat loss and transfer is due to ventilation at the open spaces under the arm, at the chest region and at the thigh. It is also due to less surface area being covered by the impermeable garment. These values are in agreement with the theory provided by Fan and Chen [77], who stated that there is a correlation between the fabric properties and thermal insulation of clothing and the trapped air within the fabrics, the air layers between the clothing and the garment construction, all of which contribute to the thermal insulation. MacCullough, Jones and Zbikowski [78] reported that the weight of a garment has very little effect on its thermal insulation. The results of this experiment confirm this, showing that there is no large difference in $R_{ct}$ due to fabric weight variations, since all aprons have a similar value for thermal resistance even though their weights are different (Table 5-1).
5.3.2 Evaporative resistance of body regions

Moisture vapour permeability in garments can be altered at either the manufacturing or finishing stages of the production process [64]. Also, the type of clothing worn by people directly affects the heat exchange between the human body and the environment. Breathable waterproof jackets and gear with Gore-Tex or membrane fabrics show high $R_{ct}$ and $R_{et}$. On the other hand, all lead aprons are impermeable, resulting in a high level of water evaporation resistance. As shown in Figure 5-2, the evaporation resistance of the clothing system with lead aprons is higher than that of the uniform without aprons, and the $R_{et}$ of the different lead aprons is almost the same, as it is the aprons’ impermeability which blocks the transportation of moisture. The lead aprons would cause a clammy and uncomfortable feeling for wearers due to their poor permeability hampering moisture transfer. The $R_{et}$ in the other zones not covered by the lead apron is much lower. This is because the moisture can evaporate from the gap between the clothing and the body.

![Figure 5-2 Evaporative resistance for manikin dressed in uniform and aprons in different body zones](image)

The breathability of fabric is its ability to allow moisture vapour to be transmitted through the material. According to Hohenstein’s table [79], any data + 30 of $R_{et}$ value is considered not breathable and uncomfortable to wear. Figure 5-2 reveals that the hip and stomach areas of all of the aprons have a relatively high $R_{et}$. This means the wearer
would feel an unsatisfactory sensation in these regions, with humidity and discomfort, and their tolerance time would likely be short. The $R_{et}$ varies greatly in different zones of the clothing system. The shoulder, back and thigh zones indicate a lower $R_{et}$ value due to the lead apron not covering these areas, as shown in Figure 3-6.

On the other hand, the $R_{et}$ of the stomach, chest and hip regions, showing around 250, 122, and 180 m$^2$-Pa/W, respectively, are much higher than for those regions where the uniform alone is worn. The EL apron shows a slightly higher $R_{et}$ than the other two aprons at the stomach and hip zones in particular, due to the relatively greater thickness of the EL. These results reveal that the moisture will be trapped in these zones, making the wearer clammy. It can also be estimated that the front of the aprons would generate a high level of heat stress according to the $R_{et}$ value [80]. Greyson [81] and Havenith [73] reported similar findings in that, as garment thickness increases, more air is trapped in the garment, resulting in increased resistance to heat and water vapour. The studied aprons are impermeable in specific zones, thus a high $R_{ct}$ and $R_{et}$ in those zones.

5.3.3 Stiffness of lead aprons

Flexural rigidity is an important factor that affects the handling of clothing, and can be measured as the resistance of the clothing to bending by external forces. Flexural rigidity is related to the stiffness of clothing, which may be felt manually, and clothing with high flexural rigidity tends to feel stiff. Table 5-2 shows that the RL apron has lower flexural rigidity than the UL and EL aprons. This might be related to the thickness and weight of the layers inside these aprons, which are much higher.

The relationship between the air gap size and rigidity of the fabric can be seen from Table 5-2; the warp stiffness was greater than the weft stiffness, showing anisotropy, except for the lead garment or sheet, because the lead samples were made from a different process, and there were no warp and weft yarns woven in the sheet. The coated nylon resulted in more stiffness and when there were increases in the number of layered sheets of the aprons, the drapability decreased. Lu and Song [82] in agreement with our study also indicated that adding layers decreased fabric drape and clothing folds, resulting in increased average air gaps.

The bending modulus is related to the degree of stiffness where the thickness is understood simultaneously as the resistance to bending. Thus, the bending modulus may be regarded as feeling ‘full’ or, conversely, ‘papery’. Two fabrics may have the same
flexural rigidity but if there is a marked degree of difference in thickness, the thicker fabric will have a lower bending modulus and will be regarded as the ‘fuller’ of the two [83]. It can be seen from Table 5-2 that the RL apron has a much lower bending modulus than that of the EL apron. Both the UL and EL aprons have similar flexural rigidity, which is 845 and 901 μN.m, but the EL has a greater thickness of 2.42 mm and a bending modulus of 72 μN/m² (Table 5-1, Table 5-2). It is noted that the RL apron has the lowest bending modulus owing to its highest weight of 7408 g/m². Generally, all the lead aprons (RL, UL and EL) in the experiment have high flexural and bending rigidity, so that the aprons are stiff and more likely to feel uncomfortable to wear for a prolonged period of time. Added to that, the nylon fabric which is the casing material showed a higher G and q in both directions, 20 μN.m and 41 μN/m² warp and 61 μN.m and 125 μN/m² weft, which represents a stiff texture for this type of material.

Table 5-2 Flexural rigidity and bending modulus for lead aprons

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>G = flexural rigidity (G)</th>
<th>q = bending modulus (q)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(μN.m)</td>
<td>(μN/m²)</td>
</tr>
<tr>
<td>RL</td>
<td>177</td>
<td>6.5</td>
</tr>
<tr>
<td>UL</td>
<td>901</td>
<td>30</td>
</tr>
<tr>
<td>EL</td>
<td>845</td>
<td>72</td>
</tr>
<tr>
<td>Nylon warp</td>
<td>20</td>
<td>41</td>
</tr>
<tr>
<td>Nylon weft</td>
<td>61</td>
<td>125</td>
</tr>
</tbody>
</table>

5.3.4 Garment fit analysis and air gap size measurements

It can be observed from the 3D point cloud in Figure 5-3 that the air gap between the clothing and the body was slightly different for different aprons. Due to its low thermal conductivity, static air between the body and the clothing system can block the thermal energy transfer between the skin and the surrounding atmosphere [84]. The distribution and size of the air layers between the fabric surface and the skin depend on garment size, design, ease and fit, and garment drape, as well as whether the garment has pockets, collar folds or openings at the neck [85].
Figure 5-3 3D point cloud data: (a) unclothed front; (b) side unclothed; (c) medical scrub uniform front; (d) uniform side; (e) uniform + RL apron front; (f) side of uniform + apron

Figure 5-4 shows the air gap size range in different areas of the clothing system. The chest area shows the smallest air gap, suggesting that the garment in this area fits more snugly than in other areas due to the heavy load from the apron on the chest area. Figure 5-4 also shows that the largest air gap is at the waist, where it is 64 mm for the uniform, 67 mm for the RL apron, 66 mm for the UL apron and 65 mm for the EL apron. These results show that the air gap layers are not distributed evenly over the manikin’s body. In some areas the protective garment is close to the body, while in other areas (such as at the waist) the garment is a large distance from the body.
The air gap increases significantly when the lead aprons are worn, as shown in Figure 5-4. This is due to the many layers of uniform and bulky, stiffer lead aprons. Since air has very different thermal and moisture transfer properties than fabric, it can be inferred that the air gaps trapped in the specific areas of the chest, waist and hip, as well as the thickness of the clothing and apron layers, have a critical effect on thermal resistance and evaporative resistance.

### 5.3.5 Pressure distribution for lead aprons

Lead aprons can be a burden to wearers due to their heavy weight, but there is no study so far on the effect of load pressure distribution on the overall performance of a medical practitioner. Figure 5-5 shows the different pressure loads for the aprons tested. The RL apron shows the highest-pressure load with 22.5 mmHg, followed by the UL apron with 20 mmHg and the EL apron with 19 mmHg. The trend is greatly related to the weight of the lead aprons: the heavier the apron, the higher the pressure. It was found that all of the aprons show a relatively high-pressure load on both shoulders, which can negatively affect the overall comfort of the wearer. Practitioners standing for longer procedures will suffer from tiredness and fatigue caused by the load on their shoulders (see Appendix 1).
5.4 Conclusion

Lead aprons showed high thermal and evaporative resistances due to the impermeable garment components and the thick layers within the aprons. All the selected aprons were heavy, between 3.76 and 3.04 kg, which will cause discomfort to the shoulders and back of wearers, in particular for surgery and other procedures of long duration. All lead aprons have a high level of stiffness, which makes the wearer of the aprons feel hard to move and perform their usual tasks in the imaging room. The average air gap size at the targeted regions (chest, waist and hip) was relatively high, indicating greater looseness in the lead aprons. Multiple pressure analysis revealed that the heavier weight aprons exhibited higher pressure loads to the shoulders.
Chapter 6: Design and Engineering of 3-D Seamless Apron for Comfort Performance Enhancement

6.1 Introduction

Radiation exposure can be harmful to human health. Therefore, radiation protection is crucial for occupational health and safety. Pregnant patients, for example, should be aware of and cautious about protecting their fetus from X-ray exposure. Female radiographers should protect their important organs, especially the breasts, which are radiosensitive [3]. Recently, shielding fabrics have been produced using matrices made of resin, nano-scale and micron-scale metallic particles. The particles are made to fuse and interlock with the fabric [86]. As a result, the interlocking produces an impermeable fabric that protects against ionising radiation [87]. One main problem of this type of apron and vest is that the fabric is not well suited for manoeuvring [88, 89]. For example, radiographers need to be able to move around and the traditional ‘flat’ shields make movement difficult.

Seamless knitting technology creates a complete garment with no cutting or sewing required. It offers an opportunity for designing and engineering female garments with different body contours. Hence, employing a 3D seamless knitting design for female aprons can produce a garment that fits to the female body structure. X-ray protective garments require a tight fit on the body of the wearer. Further, analysis of the air gaps between the clothing and body is fundamental in ensuring that the clothing fits the individual. The size of the air gaps determines two essential aspects: thermal insulation, as well as the fit of the clothing. Fitting of protective clothing onto the body figure can enhance protection performance [90].

To take advantage of seamless knitting technology and 3D body scanning technology, this chapter explores the design and production of weft-knit single jersey fabric and a 3D knitted seamless female apron designed for a true fit with a flexible textile structure.

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3 The outcomes of this chapter have been published at Proceedings of the 1st International Design Technology Conference (DesTech 2015).
6.2 Materials and Methods

The nylon/wool yarns used in fabric production have been described in Chapter 3. Figure 6-1 shows the basic medical scrub uniform which is used in hospitals by female radiographers in Saudi Arabia, on normal and pregnant manikins. The female radiographer uniform consists of a short-sleeved V-neck shirt and pants.

![Medical scrub uniform on (a) normal and (b) pregnant manikins](image)

6.2.1 Fabric design

Table 6-1 shows the weft-knitted fabric properties designed for the preparation of the prototype apron. Wales are referred to as NX and Y represents the courses [91]. The software employed was Shima Seiki Whole Garment New SES-S-WG® and the entire garment program WG-SDS-ONE APEX3 was also employed for the garment design and engineering. The developed knitted fabric was produced with an E14 gauge. The loop length on the fabric was 6.63 mm, while the tightness was 30 qualities. The ‘qualities’ tightness factor is a measure of the tightness of a fabric. The fabric was composed of 94 tex ballistic nylon filament plated with 41 tex two-fold wool yarn on the back face. The tension was controlled by the stitch setting on the machine. Nylon is known for its strength, light weight, resistance to abrasion and resistance to wear and tear. The high strength of nylon provides features such as durability. In addition, wool in the garment has various advantageous properties that include comfort, dirt and odour resistance, insulation, and resistance to wear and tear [92, 93]. Wool is also known to be non-
allergenic and it does not promote the growth of bacteria [92]; hence, it can protect the wearer from possible effects that may harm health and wellbeing.

Table 6-1 Fabric properties

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Yarn count (tex)</th>
<th>Wales/ends (NX) (/cm)</th>
<th>Courses/picks (Y) (/cm)</th>
<th>Fabric thickness (mm)</th>
<th>Mass per unit area (g/m²)</th>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nylon/wool</td>
<td>Nylon 94, wool 41</td>
<td>7.20</td>
<td>8.07</td>
<td>1.25</td>
<td>462.8</td>
<td>Single jersey</td>
</tr>
<tr>
<td>Medical scrub uniform (3 layers)</td>
<td>65% polyester, 35% cotton</td>
<td>14.5</td>
<td>12.2</td>
<td>0.40×3</td>
<td>202×3</td>
<td>Plain weave</td>
</tr>
</tbody>
</table>

### 6.2.2 3D body scanner

The models used for the 3D scanning of the female body were size 14 manikins of pregnant and normal female bodies. A 3D body scanner system made by Textile/Clothing Technology (TC)² was used to develop an accurate representation of the female body figure. The readings, that is, the measurements taken from the manikins, were used to develop a design protocol from the measurements of the aprons fit on the unclothed female body.

### 6.2.3 Air gap measurement

Both unclothed and clothed manikins were scanned. The two scans were aligned based on various nodules that shifted slightly at points X, Y, Z; see Figure 3-4. The shifting was paramount in ensuring that the clothed scans perfectly aligned with the unclothed scans. The correlation between air gaps and clothing fit can be extracted via 3D scanning technology [48]. The average air gap sizes were obtained by taking the average of three measurements of high value. The gap size was measured between the body surface and the clothing surface in mm. The aim of the investigation was mainly to ensure that the design fit perfectly on the female body.

The methods have been described in Chapter 3:

- Dry thermal resistance ($R_{ct}$)
- Evaporative resistance ($R_{et}$)
- Mass per unit area and material thickness
- Stiffness of cloth
6.3 Modelling Design

6.3.1 Sizing of female apron design

The garment to be designed presented various challenges in relation to ease of putting on and taking off depending on how tight or loose the fabric was on the body. Therefore, determining the right size of clothing for a particular body shape and size was essential if the apron was to offer comfort to the wearer. Bearing in mind that the garment design is intended for pregnant women, it was essential that all dimensions of size and body structure were considered in order to come up with an appropriate perfect fit. Figure 6-2 and Figure 6-3 illustrate the scanned images and USA sizing system measurements, which are the template standard clothing sizes for women and originally developed from a statistical data template that comes with the TC² program.
The manikins dressed in radiographer undergarments were also scanned, as shown in Figure 6-1. The measurements of the dimensions retrieved are as indicated in Table 6-2 and Table 6-3. After the measurements were taken, the parameters were converted in consideration of the density of the fabric in order to achieve a perfect fit based on the body size measurements and an estimated ease of allowance. Figure 6-2 and Figure 6-3 indicate the position numbers on the manikins which link to the measurements in Table 6-2 and Table 6-3. The eventual knitting design was based on the measurement calculations for the aprons, i.e. the numbers for NX and Y. The front design and apron knitting sizes (numbers for NX and Y) were calculated through aggregation of the clothed measurements. It also incorporated half-measurement considerations for the allowance of ease. The conversions were calculated as:

\[
\text{Length} = Y \times S,
\]

\[
\text{Width} = NX \times S,
\]

where Y represents the course numbers per cm, while NX refers to the wales, that is, the number of needles per cm. S in the equation represents the actual unclothed body size measurement in cm [91].
Table 6-2 Measurements of input parameters for normal female manikin design and apron

<table>
<thead>
<tr>
<th>Position numbered</th>
<th>Measurement (cm)</th>
<th>Estimated ease allowance (cm)</th>
<th>Knitting size (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nude manikin</td>
<td>Cloth on</td>
<td>NX and Y</td>
</tr>
<tr>
<td>1. Neck girth</td>
<td>41</td>
<td>42</td>
<td>1</td>
</tr>
<tr>
<td>2. Shoulder length – right</td>
<td>14</td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td>3. Upper bust</td>
<td>101</td>
<td>104</td>
<td>3</td>
</tr>
<tr>
<td>4. Bust girth</td>
<td>103</td>
<td>107</td>
<td>4</td>
</tr>
<tr>
<td>5. Bust to bust – horizontal</td>
<td>22.0</td>
<td>22.5</td>
<td>0.5</td>
</tr>
<tr>
<td>6. Under bust girth</td>
<td>94</td>
<td>97</td>
<td>3</td>
</tr>
<tr>
<td>7. Neck to waist length – front</td>
<td>40</td>
<td>41</td>
<td>1</td>
</tr>
<tr>
<td>8. Waist girth</td>
<td>79</td>
<td>83</td>
<td>4</td>
</tr>
<tr>
<td>9. Armhole length</td>
<td>25</td>
<td>25</td>
<td>1</td>
</tr>
<tr>
<td>10. Hip girth</td>
<td>104</td>
<td>108</td>
<td>4</td>
</tr>
<tr>
<td>11. Apron length</td>
<td>–</td>
<td>113</td>
<td>–</td>
</tr>
<tr>
<td>12. design length</td>
<td>–</td>
<td>46</td>
<td>–</td>
</tr>
</tbody>
</table>

* ½ the girth size converted to NX

Table 6-3 Measurements of input parameters for knitting of pregnant female full-front apron

<table>
<thead>
<tr>
<th>Position numbered</th>
<th>Measurement (cm)</th>
<th>Estimated ease allowance (cm)</th>
<th>Knitting size (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unclothed manikin</td>
<td>Clothed</td>
<td>NX and Y</td>
</tr>
<tr>
<td>1. Neck girth</td>
<td>38</td>
<td>39</td>
<td>1</td>
</tr>
<tr>
<td>2. Shoulder length – right</td>
<td>13</td>
<td>13</td>
<td>1</td>
</tr>
<tr>
<td>3. Upper bust</td>
<td>97</td>
<td>100</td>
<td>3</td>
</tr>
<tr>
<td>4. Bust girth</td>
<td>99</td>
<td>103</td>
<td>4</td>
</tr>
<tr>
<td>5. Bust to bust – horizontal</td>
<td>17</td>
<td>18</td>
<td>1</td>
</tr>
<tr>
<td>6. Under bust girth</td>
<td>87</td>
<td>90</td>
<td>3</td>
</tr>
<tr>
<td>7. Neck to waist length – front</td>
<td>34</td>
<td>35</td>
<td>1</td>
</tr>
<tr>
<td>8. Waist girth</td>
<td>106</td>
<td>110</td>
<td>4</td>
</tr>
<tr>
<td>9. Armhole length</td>
<td>23</td>
<td>23</td>
<td>1</td>
</tr>
<tr>
<td>10. Hip girth</td>
<td>107</td>
<td>111</td>
<td>4</td>
</tr>
<tr>
<td>11. Apron length</td>
<td>–</td>
<td>113</td>
<td>–</td>
</tr>
</tbody>
</table>

* ½ the girth size converted to NX

6.3.2 Knitting package

To develop the apron design, the Knit-Paint program was applied to create the 2D surface of the structured pattern. This knitting package consists of three basic packets that are crucial to the process of 3D knitting: first it consists of the base pattern, second the compressed pattern and third the development pattern. The three patterns are...
essential in the delivery of a complete package. In that regard, the knitting kit is useful in the development of visualised and communicated patterns between 3D and 2D seamless knitting [94]. Colour-coding is a central part of the 3D knitting process in which the 3D seamless knitting process takes shape. The 3D apron design incorporates all features of the female body and encompasses 2×2 ribs both for the round collar and for the hem rib. It also contains bust cup packages. The maternity apron includes adjustments that focus primarily on the abdominal area to allow room for the protrusion of the pregnancy (see Appendix 2).

A detailed depiction of the 2D design after completion is given in Table 6-4. It shows the different style of each design for the open cup with a round collar panel; a unique 2D design for the bustline which can be opened and closed was created separately. For the front apron and maternity front apron a 3D shape was created in the bust area via darts. This style consists of two darts starting from each armhole side and then increasing smoothly to the bust point. For the maternity apron, at the abdominal there is also a dome shaped under the bustline. All the designs have round collars to protect the radiosensitive thyroid area.
<table>
<thead>
<tr>
<th>Knitting package</th>
<th>Open cup with round collar panel</th>
<th>Front apron</th>
<th>Maternity front apron</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2D compressed pattern) designs for the seamless panel and aprons</td>
<td><img src="Image" alt="Open cup with round collar panel" /></td>
<td><img src="Image" alt="Front apron" /></td>
<td><img src="Image" alt="Maternity front apron" /></td>
</tr>
</tbody>
</table>

3D seamless knitting designs

| Strapping | ![Strapping](Image) | ![Strapping](Image) | ![Strapping](Image) |
| Shoulder widening | ![Shoulder widening](Image) | ![Shoulder widening](Image) | ![Shoulder widening](Image) |
| Cup | ![Cup](Image) | ![Cup](Image) | ![Cup](Image) |
| Armhole shaping | ![Armhole shaping](Image) | ![Armhole shaping](Image) | ![Armhole shaping](Image) |
| Round collar 2×2 rib | ![Round collar 2×2 rib](Image) | ![Round collar 2×2 rib](Image) | ![Round collar 2×2 rib](Image) |
| Abdominal area | ![Abdominal area](Image) | ![Abdominal area](Image) | ![Abdominal area](Image) |
| Body | ![Body](Image) | ![Body](Image) | ![Body](Image) |
| Open cup | ![Open cup](Image) | ![Open cup](Image) | ![Open cup](Image) |
| Hem 2×2 rib | ![Hem 2×2 rib](Image) | ![Hem 2×2 rib](Image) | ![Hem 2×2 rib](Image) |
6.4 Results and Discussion

6.4.1 3D Knitting technology of different design features and characteristics

A common 2D compressed pattern, which is the complete version of a design, was used for all the designs and in the creation of a 3D shape via the transfer stitches technique; see Table 6-4. The transfer alters the shape and size of the fabrics and eventually develops the shape [94]. The development pattern is the expanding process of the base and compressed pattern combined together to achieve the overall knitting process, as shown in Table 6-4. An important feature of the design is that it can be worn either on top of a uniform such as medical scrubs or just underclothing, or directly on the body without any underclothing. A half-ease allowance is helpful in increasing the front garment in the absence of undergarments. Subsequently, increasing the cup darts in the 2D design required the addition of an NX number to the start and the end. This was done in order to determine the width needed for the bust and hip regions.

The process was then repeated several times for other parts of the body such as the abdominal regions, bearing in mind that the central objective was to achieve the smooth and soft shape of a dome. The procedure was similar for the length of the design, although quite different from the front apron process. An analysis of the design’s effectiveness as observed from the 3D scans revealed that the designs fit well on both pregnant and non-pregnant manikins. In the same way, there were other factors that required consideration such as comfort, style, duration, purpose, wear etc. Table 6-5 shows a collection of the features and characteristics of garment designs for females that can help in understanding the purpose and function of each design. The second column displays the 3D body scanning results for the unclothed manikin and then the manikin with the newly designed apron, then for the other designs with uniform and apron.
Table 6-5 Female garment design features and characteristics

<table>
<thead>
<tr>
<th>Design feature</th>
<th>3D body scanning</th>
<th>Function of design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open cup with round collar design</td>
<td>![Image]</td>
<td>• (a, b) This design can be used for mammography examinations.</td>
</tr>
<tr>
<td></td>
<td>![Image]</td>
<td>• For women who suffer from breast cancer or need to go for radiation therapy.</td>
</tr>
<tr>
<td></td>
<td>![Image]</td>
<td>• (a, b, c, d) The open cup design feature helps to open one side of the breast to be exposed to the radiation, while covering the other side with a bra pad to provide more protection to this sensitive organ from scatter or leakage radiation.</td>
</tr>
<tr>
<td></td>
<td>![Image]</td>
<td>• Radiation therapy is usually dependent on tumour size in cm; for one study the planned target volume was defined as the whole breast with a 1 cm margin to palpable breast tissue, where regional radiotherapy was indicated [95].</td>
</tr>
<tr>
<td></td>
<td>![Image]</td>
<td>• Open cup with round collar design can be worn by female patients on the upper torso without any clothing underneath.</td>
</tr>
<tr>
<td></td>
<td>![Image]</td>
<td>• This design is joined with strips on each side and from the shoulder line. The round collar adds more protection to the thyroid area.</td>
</tr>
<tr>
<td></td>
<td>![Image]</td>
<td>• The (e) bra pad design completes the design.</td>
</tr>
<tr>
<td>Round neck front apron design</td>
<td>![Image]</td>
<td>• This design offers full protection in CT and fluoroscopy examinations for female radiographers.</td>
</tr>
<tr>
<td></td>
<td>![Image]</td>
<td>• (a, b and c) This design can be worn on top of medical scrub.</td>
</tr>
<tr>
<td></td>
<td>![Image]</td>
<td>• The round collar protects the thyroid area from scatter radiation.</td>
</tr>
</tbody>
</table>
Design feature | 3D body scanning | Function of design
---|---|---
Maternity front apron design | | • This design offers full protection in CT and fluoroscopy examinations for pregnant radiographers.
| | • This design can be worn on top of medical scrub.
| | • The round collar protects the thyroid area from scatter radiation.

6.4.2 Fabric properties

The knitted fabric thickness is 1.25 mm, as shown in Table 3-3. The mass per unit area for the nylon/wool fabric is 462.8 g/m², which is coincidentally a medium weight. The wool yarn was plated on the back of the fabric; see Figure 6-4. In addition, a 94 tex filament nylon yarn was knitted on the front face of the fabric. This combination of two yarns and the knit structure resulted in a thicker fabric. The fibre used does not have much radiation-shielding capability. This design is intended to demonstrate the concept only. These unique properties prepare the base garment for future coating with absorber materials. The tight structure of the garment and plated wool improve the moisture absorbency because the wool side will be next to the skin. Since this fabric is designed to be a backing material, it has two faces: the outer face of nylon to hold the absorber material, and the inner face of wool next to the skin.
6.5 Comfort Performance of Developed Knitted Design

The female apron design and breast panel were tested using the thermal manikin to measure the thermal and water-vapour conductivity. The testing methods and instruments have been described in Chapter 3.
6.5.1 Dry thermal resistance

Figure 6-6 Thermal resistance in different body zones for thermal manikin dressed in uniform and front and open cup aprons

Figure 6-6 reveals that the developed front apron has high thermal resistance due to the wool plated at the back, but wool has the capacity to absorb moisture. It can be seen from the chart that the thigh and shoulder show lower \( R_{ct} \) values, which mean low thermal resistance, followed by the chest and back, which have slightly higher \( R_{ct} \) values, then the stomach and hip with the highest \( R_{ct} \) values. This displays that some heat can be kept within the cloth layers without passing to the outer atmosphere. This may be beneficial for normal clothing because usually medical practitioners work in well-ventilated spaces or cold temperatures. However, it can be a disadvantage at the same time when the aprons are coated with X-ray absorbers, resulting in poor heat transfer and very bulky and heavy apron that causes discomfort to the medicinal practitioners.

It is worth noting that because both styles, the breast panel and apron, have the same structure and the same fibre quality, the fabric thermal resistance should be similar in all body zones. It is normal that the shoulder and thigh are both between 0.23 and 0.26 m\(^2\cdot{^\circ}\)C/W. This is attributable to the one layer of fabric in that zone, which allows more air to pass through. The chest and back increase slightly to 0.30 m\(^2\cdot{^\circ}\)C/W for the panel.
and 0.35 m²·°C/W for the apron. The last group, the stomach and hip, achieve the highest thermal resistance of 0.48 m²·°C/W for the panel and 0.58 m²·°C/W for the apron. This is due to three or more cloth layers in that particular area, plus the belt of the pants and the belt of the apron and panel. This means the designs fit the manikin very closely in those specific zones; the air gap measurement data emphasises that the waist area showed the smallest air gap (see Figure 6-8). Smaller air gaps can lead to increasing the thermal resistance in the stomach and hip areas, helping to keep the wearer feel a warm sensation, particularly during long procedures. We can conclude that the clothing system has important effects on the thermal insulation.

### 6.5.2 Evaporative resistance

![Figure 6-7 Evaporative resistance in different body zones for thermal manikin dressed in uniform and front and open cup aprons](image)

Figure 6-7 shows the evaporative resistance results with a uniform and the two developed styles tested on the thermal manikin. The shoulder and chest zones show the lowest $R_{et}$ values, followed by the thigh and back group, which display the highest $R_{et}$ values. These findings suggest that both designs have a similar trend of evaporative resistance. The shoulder and chest have 27.7 m²·Pa/W for the panel and 29.4 m²·Pa/W for the apron.
for the apron. A lower $R_{et}$ value means a better evaporative transfer, allowing the moisture to evaporate through the fabric. The thigh and back zones show higher $R_{et}$ results of $45.9 \text{ m}^2 \cdot \text{Pa/W}$ for the panel and $49.5 \text{ m}^2 \cdot \text{Pa/W}$ for the apron. This is due to the material properties: most medical uniforms have more polyester synthetic fibre; polyester is not a breathable fabric and has poor moisture absorption ability, so perspiration and heat are trapped next to the skin. Wearers often feel sticky and clammy in humid weather. The stomach and hip zones have the highest level of evaporative resistance, which means they provide an uncomfortable sensation due to the moisture staying between the fabric and skin and not evaporating into the outer environment. In other words, the fabric does not allow moisture to evaporate through its structure so as to pass into the outer environment in order to cool the body. At the hip zone, the panel indicates $90.7 \text{ m}^2 \cdot \text{Pa/W}$ and the apron $93.3 \text{ m}^2 \cdot \text{Pa/W}$.

6.5.3 Air gap measurement

FreeCAD software was used for analysis of the air gaps between the unclothed manikin and the garments based on the measurements of the bust, waist and hip. An analysis of the garment fit was achieved through alignment of the unclothed and clothed scans of the manikins by overlapping them. Good alignment of the two means that minimal changes were made in the positions of the clothed and unclothed scans. Figure 6-8 shows the average minimum and maximum air gap sizes in mm of all the garments developed.

The waist measurement indicates the smallest air gap between the body and clothing layers by $14 \text{ mm}$ for the open cup design; it is noted that this design should be worn on the body without clothing underneath. The air gap was $15 \text{ mm}$ for the front apron on the normal manikin and $21 \text{ mm}$ for the pregnant manikin. These small values for the air gap size ensure that the fabric in the waist region fits better than in other regions. The waist girth achieved by this data might be because of the thin layer of the T-shirt uniform under the apron, which was $0.40 \text{ mm}$. Also, the belt included with the design to provide more fitting to the female body profile helped to achieve the smallest air gap size in that particular area, as it can be tightened or made loose via the belt tie.

There was a large air gap size at the hip region for the pregnant manikin due to the slight loosening at the abdominal area, which represents about $25 \text{ mm}$ and $18 \text{ mm}$, high values for the front apron design. The large air gaps result for two reasons: the first is the two
layers or more of the uniform system, T-shirt 0.40 mm and pants 0.40 mm, and the second is the body posture and design structure, which make the garment hang out from the body, as seen in Table 6-5.

The chest measurement showed the largest air gap size for the pregnant manikin with 32 mm, then the normal manikin with 25 mm. The reason for these large air gaps is the slight looseness of these designs, because there are three or more garment layers (bra + T-shirt + apron/breast panel) on the chest area that create the gaps underneath and the drape of the aprons. Also, the body posture and body part geometry of the manikin shows a large girth in the chest area. The open cup design displayed the lowest value, with 18 mm for the chest girth. It should be noted that the open cup design was placed on the normal manikin without any clothing underneath, because this design would be next to the skin for mammograph examinations.

It is also worth noting that there are no recommendations in the literature for determining the perfect air gap size in aprons as protective clothing. The fit depends on several factors: the body posture, body part geometry, as well as garment layers plus stiffness and drape.

![Minimum and maximum air gap size (mm)](image)

**Figure 6-8 Maximum and minimum air gap sizes (mm) from three different scan slices**

Calculations of the hip girth were made for the front apron as well as for the maternity apron; the average of three measurements between the body surface and the clothing
surface was taken into consideration for the highest value. In the case of the front apron the average measurement taken was 18 mm, while the highest value was 25 mm. The three designs of the front, maternity and non-maternity aprons reveal that the average air gap is larger than in the open cup design. This is due to the medical scrub uniform worn underneath, which was found to decrease the drape of the fabric owing to wrinkles on the undergarments worn beneath the apron. Coupled with these clothing folds, the average air gap of the aprons increased. Therefore, there is a need for further analysis of the common effects of fabric properties like stiffness, drape and clothing size on the air gap size.

Furthermore, the number of fabric layers was also crucial during the analysis, as various characteristic features e.g. flexibility and elasticity, affect the size of the air gaps that are entrapped within [96]. The air gap and the thermal insulation had a directly proportional relationship: when an air gap exceeded 1 cm, the thermal insulation decreased, and vice versa [97]. In addition, further study is needed to determine what maximum size of air gap is adequate for well-fitting protective clothing and how this can provide a good level of protection. Several combinations of fabric/fibre composition, physical and mechanical properties of fabrics, number of layers, design of clothing, heat flux, air volume and moisture present can have a great impact on thermal comfort and can also affect the required thickness of the air layer [90, 97] [98].

### 6.6 Conclusion

This chapter has developed three unique basic designs of garments for protecting medical workers and patients from radiation exposure. Based on study and analysis of measurements of the female body, this chapter presents alternative aprons to be coated with X-ray absorber chemicals that can be worn by females in the future. The three designs, namely, an open breast cup with round collar design, front apron and maternity apron, are suited to the female body features, mainly the breast, waist and hip regions.

Two designs plus the medical scrub uniform have been investigated for thermal and water-vapour conductivity using a thermal manikin. The results show that the developed aprons have a reasonable thermal conductivity and water vapour transfer ability to transfer the moisture to the outer atmosphere due to the plated wool at the back and nylon fabric at the front. The garment design is based on 3D scan measurements of the female body to put into perspective the features of the female body. As a result, the
designed garments fit smoothly on female body curves in sensitive areas like the chest and abdomen, and on the entire body for female workers, since the designs are tailored to incorporate all the features of the female body contour. Coating of fabrics for the developed designs will be reported for radiation-shielding performance in Chapter 7. The full produced garment designs could be coated with the radiation-absorber materials for shielding against X-rays.
Chapter 7: X-ray Shielding Performance of Fabrics Coated with Multiple Radiation Absorbers

7.1 Introduction

X-rays have gained prominence as a diagnostic tool in the medical field [99]. More than 3 billion X-ray exposures are made every year for medical diagnoses worldwide [100]. X-rays are ionising radiation produced by X-ray equipment used for medical imaging. Although controlled radiation can save lives when used in diagnostic and therapeutic procedures, uncontrolled scattered radiation can cause harm to human cells and hence destroy tissues and organs. It is evident that ionising radiation increases the risk of cancer [101]. Therefore, radiation protection is an important issue in the medical imaging industry.

Lead as a heavy metal is toxic. Lead poisoning is one of the oldest forms of contact with toxins. In the modern world where the uses of lead have been reduced to the bare minimum, it has become necessary to limit its manufacture and use in X-ray protective garments. In July 2014 the European Union placed a ban on the use of lead in healthcare in Europe [102]. This has further created the need for alternative materials to lead aprons.

Composite materials combine a number of properties that are not usually available in a single material. The ultimate goal is that composites will use less lead and combine X-ray shielding with low weight [103]. Some of these lightweight materials are achieved using nano-particles in composite matrices. In recent years, the use of nano-particles in X-ray protective aprons has gained momentum. In fact, some of these new materials have been successfully included in polymer matrices for X-ray and γ-ray shielding materials [104, 105]. Examples of possible radiological protective garments with nanostructured materials include lead-free aprons, which can also be lighter than the usual ones [18, 106].

4 The outcomes of this chapter have been published in Textile Research Journal 2015 and Fibers and Polymers 2016.
Lead and a few other heavy metals are known to offer effective X-ray protection. New polymer composites for radiation shielding continue to be fabricated and tested by various researchers [103], [107], [108]. For example, lead monoxide–polyester [108] and lead oxide–isophthalic resin [109] have been reported for γ-radiation shielding purposes. The new generations of aprons are represented mostly by mixtures of different metals, including antimony, tin, tungsten, barium and bismuth, to provide the same function as lead in blocking radiation. These metals are all heavy metals and bring with them new complications such as environmental concerns [110]. Nevertheless, these new technologies are able to reduce apron weight by up to 30% compared to a conventional lead sheeting apron [18]. They show equal or better lead equivalence (mm Pb), which provides the standard for comparing materials and is an indication of the X-ray protectiveness of the material [18].

Nambiar et al. [107] prepared polydimethylsiloxane (PDMS) composites with different mixtures of high atomic number compounds, including bismuth tungsten oxide (BTO) and bismuth oxide (BO) for X-ray protection. It was found that PDMS composites with 36.36 wt% BTO had an increase of 50% attenuation compared to PDMS-only materials. The researchers concluded that a composite sample with 60.6 wt% BO offered the best protection, at 92.5% attenuation for a beam produced at a tube potential of 60 Kv [107]. In another publication, Nambiar et al. [103] also found that a PDMS/BO nanocomposite with 44.44 wt% BO was equally capable of attenuating an X-ray beam produced at 60 kV, which is a beam commonly used in interventional radiology (IVR) procedures.

The use of barium sulphate (BaSO₄) as a good absorber material for X-ray protection has been reported [111-114]. For example, Fukushi found that a combination of barium sulfate and calcium sulfate with a weight ratio of 1:1 can provide excellent X-ray shielding ability [113]. In addition, BaSO₄ is relatively inert, nontoxic, environmentally friendly, harmless to the human body and easy to mix with other compounds [111]. More importantly, BaSO₄ has a high coefficient for absorption of radiation, making it suitable for use in shielding from X-rays and γ-rays [3, 111].

The efficiency of novel X-ray attenuators can be evaluated using a computer program called XCOM code, which provides detailed and updated references to the literature from which numerical approximations are derived. The XCOM database gives photon cross-sections for scattering, photoelectric absorption and pair production, as well as total attenuation coefficients for any element, compound or mixture (Z ≤ 100) at
energies from 1 keV to 100 GeV. Total attenuation levels reported at different energy edges are based on tabulated photon cross-sections and attenuation coefficients carrying absorptive and deflective characteristics of known atomic compositions [115, 116]. XCOM simulations can identify unleaded mixtures [105].

Antinomy (Sb) in combination with different metal absorbers aluminium (Al), tin (Sn), tungsten (W), lead (Pb) and bismuth (Bi) have been used for radiation-shielding purposes [117]. Lin et al. [118] created a shielding vest to increase the shielding efficiency of X-ray protection using different metal powders, such as lead (Pb-82z), silicon (Si-14z), titanium (Ti-22z) and antimony (Sb-51z). They found that all X-ray shielding powders with a particle size less than 500 μm helped dispersion into a polymer resin. These powders were coated onto sandwich air mesh fabric (SAMF) to form a shielding sheet. They concluded that X-ray shielding effectiveness was proportional to the quantity of the powders. The SAMF provided flexibility to the protective vest [118]. Several attempts were made by Maghrabi et al. to coat bismuth oxide [63] and barium sulphate [119] as an alternative material to lead onto nylon and polyester woven fabrics for X-ray protection (see Sections 7.3.1 and 7.3.2, Chapter 7). It is expected that the coated fabrics would have higher durability and flexibility than the SAMF fabric, and could be cut and formed into any size to accommodate different body shapes, such as the curvatures of a female body [62].

A considerable amount of research literature has been published on X-ray shielding material using bismuth oxide (Bi₂O₃) as a replacement material for lead. For example, Schmid et al. [120] investigated the effectiveness of different shielding materials in protective clothing using dicentric frequency chromosomes in human peripheral lymphocytes as a marker of radiation-induced damage. Blood samples from a healthy donor were exposed to 70 kV X-rays behind lead shielding materials, tin/antimony and bismuth barrier/tin/tungsten (Bi + Sn + W) with the same nominal lead-equivalence value of 0.35 mm Pb. Their study indicated different yields of dicentrics in human lymphocytes exposed to the broad spectrum of diagnostic 70 kV X-rays immediately behind commercially available non-lead based shielding materials in radio-protective clothing. Tin and antimony could significantly reduce the shielding property associated with a significant increase in the maximum relative biological effectiveness with respect to lead, whereas a shielding material with an especially fluorescent blocking layer of
bismuth, such as bismuth barrier/tin/tungsten, could avoid this undesirable problem in radiation protection [120].

The design of the backing material of garments used for shielding X-rays is crucial. Studying the physical, mechanical and aesthetics properties of the material can give a good indication of the expected outcome of the fabric efficiency. Fabrics made from natural and manufactured fibres have been extensively used for clothing, workwear and industrial applications; the physical and mechanical properties of these fabrics are affected by the fibre type, yarn construction and fabric structure, as well as any treatment that may have been applied to them. A range of fabric performance parameters are assessed for different end-use applications. Fabrics are heterogeneous materials and the test results differ when a fabric specimen is tested in different directions (e.g. warp or weft for woven, course or wale for knits). While different test standards are applied to different types of fabrics, it is important to note that three important factors for any test are the sampling protocol, the measurement conditions, and the instrumentation and measurement procedure [56]. According to the literature, there are few studies evaluating textile materials for shielding from radiation. A majority of studies focus on the shielding performance and overlook the garment’s physical, mechanical and aesthetic properties. As a result, this chapter looks at the physical, mechanical and aesthetics properties of textiles to benefit the medical field for both shielding and durability.

7.2 Experimental Design

Two main types of textile structure were used in this experiment, woven and knitted. All the details of these structures have been listed in Chapter 3. The radiation absorbers and their properties can be seen in Table 7-1.
Table 7-1 Chemical composition of antimony pentoxide, barium sulphate and bismuth oxide

<table>
<thead>
<tr>
<th>Metal type</th>
<th>Atomic no. (Z)</th>
<th>Atomic mass (amu)</th>
<th>(σ) Atomic cross-section (pm)</th>
<th>Compound formula</th>
<th>Mole wt. (g/mol)</th>
<th>Particle size (μm)</th>
<th>% by mass of elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antimony (Sb)</td>
<td>51</td>
<td>121.75</td>
<td>145</td>
<td>Antimony Pentoxide (Sb₂O₅)</td>
<td>323.5</td>
<td>0.04</td>
<td>75.27</td>
</tr>
<tr>
<td>Barium (Ba)</td>
<td>56</td>
<td>137.33</td>
<td>215</td>
<td>Barium (II) sulphate (BaSO₄)</td>
<td>233.4</td>
<td>~1</td>
<td>58.84</td>
</tr>
<tr>
<td>Bismuth (Bi)</td>
<td>83</td>
<td>208.98</td>
<td>160</td>
<td>Bismuth (III) oxide (Bi₂O₃)</td>
<td>466.0</td>
<td>10</td>
<td>89.70</td>
</tr>
</tbody>
</table>

The test methods used in this study were:

- X-ray protection measurement
- Mass per unit area
- Material thickness
- Scanning electron microscopy (SEM)
- Total mass attenuation coefficient analysis
- Stiffness of coated samples
- Abrasion resistance of coated samples
- Stretch and recovery properties of coated samples

All these methods have been discussed in Chapter 3.

7.3 Results and Discussion

7.3.1 Bismuth oxide-coated fabrics for X-ray shielding

7.3.1.1 Coating method

The polyester and nylon fabric samples were coated using three different application levels of Bi₂O₃ and PVC resin using a knife-edge coater. Details of the coating are shown in Table 7-2. For example, 30 g of Bi₂O₃ and 100 g PVC were mixed in a blender for 15 min. to become consistent. The mixture was then coated on fabric specimens using a similar amount of coating for each sample. Six different samples were coated using the
formulation developed, and the fabrics were then dried at 60 °C and further cured at 150 °C in an oven for 5 min.

Table 7-2 Coating description (BO= Bi₂O₃; N= Nylon; P= Polyester; PVC= polyvinyl chloride)

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Coating formulation (g)</th>
<th>% BO in coating material</th>
<th>Base fabric weight (g/m²)</th>
<th>Weight of coated fabric (g/m²)</th>
<th>Applied coating weight (g/m²)</th>
<th>Weight of BO on fabric (g/m²)</th>
<th>Weight of bismuth on fabric (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BN1</td>
<td>100 PVC + 30 BO</td>
<td>23.1</td>
<td>315.4</td>
<td>1392.6</td>
<td>1077.2</td>
<td>248.6</td>
<td>223.0</td>
</tr>
<tr>
<td>BN2</td>
<td>100 PVC + 30 BO</td>
<td>23.1</td>
<td>315.4</td>
<td>2314.4</td>
<td>1999.0</td>
<td>461.3</td>
<td>413.9</td>
</tr>
<tr>
<td>BP1</td>
<td>100 PVC + 100 BO</td>
<td>50.0</td>
<td>149.2</td>
<td>1972.6</td>
<td>1823.4</td>
<td>911.7</td>
<td>817.8</td>
</tr>
<tr>
<td>BP2</td>
<td>100 PVC + 100 BO</td>
<td>50.0</td>
<td>149.2</td>
<td>2422.6</td>
<td>2273.4</td>
<td>1136.7</td>
<td>1019.6</td>
</tr>
<tr>
<td>BP3</td>
<td>100 PVC + 200 BO</td>
<td>66.7</td>
<td>149.2</td>
<td>1978.6</td>
<td>1829.4</td>
<td>1219.6</td>
<td>1094.1</td>
</tr>
<tr>
<td>BP4</td>
<td>100 PVC + 200 BO</td>
<td>66.7</td>
<td>149.2</td>
<td>2907.0</td>
<td>2757.8</td>
<td>1838.5</td>
<td>1649.2</td>
</tr>
</tbody>
</table>

Note: the 'weight of BO on fabric' was calculated by assuming no weight changes before or after PVC curing.

As with most PVC-based textile coatings, there were no difficulties in applying Bi₂O₃ particles onto the fabrics. Figure 7-1 shows that the Bi₂O₃ particle distribution on the fabric surface appears homogenous. However, at a high Bi₂O₃ concentration in a PVC matrix, the homogeneity seems to be poor, as an aggregation due to agglomerates of the particles can be clearly observed in Figure 7-1(c).

Figure 7-1 Optical microscopic images: (a) nylon fabric sample coated with 23.1% Bi₂O₃; (b) polyester fabric sample coated with 50.0% Bi₂O₃; (c) polyester fabric sample coated with 66.7% Bi₂O₃
7.3.1.1 X-ray protection measurements

Initial X-ray exposure was measured without any fabric and this was taken into consideration as the control. The two fabrics without any treatment were also measured as a reference for comparison against the coated samples. Different amounts of Bi$_2$O$_3$ were coated on the fabrics and their effectiveness in shielding a medium level of radiation at 80 kVp was measured. The results are shown in Figure 7-2. The value of the transmittance corresponds with the proportion of X-rays that penetrated through the specimen, and indicates the shielding effectiveness of bismuth. A higher transmittance value corresponds to lower X-ray absorption, meaning that the sample is less effective for radiation protection.

From Figure 7-2, it is evident that the control and the uncoated fabric samples transmitted all of the X-rays and cannot be considered as having any radiation-shielding effect. Based on this fact, fabric characteristics were not studied and the same chemical concentrations did not apply to the nylon fabric as to the polyester fabric in this study. Instead, the weight of Bi$_2$O$_3$ on a fabric was mainly considered (Table 7-2).

The Bi$_2$O$_3$-coated fabrics shielded some X-rays. The transmittance values for Lite Lead and Regular Lead were 18% and 17% respectively. Samples BP2, BP3 and BP4 had similar or better X-ray shielding performance. In general, Bi$_2$O$_3$ is cheap. Although lead oxide is even cheaper than Bi$_2$O$_3$, the environmental benefit outweighs the small savings for lead oxide. Therefore, Bi$_2$O$_3$-coated fabrics could be an alternative to lead sheets due to its lower toxicity than lead.
The results in Figure 7-3 demonstrate that X-ray attenuation improved with an increase in the amount of bismuth coated on the fabric sample. Sample BN1 transmitted 67% of X-rays because the amount of Bi$_2$O$_3$ applied to this fabric was only 248.6 g/m$^2$, comparatively lower than for the other samples. In comparison, sample BN2 had nearly twice the amount of Bi$_2$O$_3$ (461.3 g/m$^2$) and reduced transmittance by 46%. The weight gains for these samples after applying the coatings were 342% for BN1 and 634% for BN2, compared to the uncoated nylon fabric.
All of the polyester-coated samples had higher concentrations of Bi$_2$O$_3$ when compared to the nylon-coated samples (Table 7-2). BP1 and BP2 were coated with the same concentration of Bi$_2$O$_3$, but different application levels. When comparing BP1 and BP2, the latter gave a better shielding effect, which is as expected because of the higher amount of coating material by 25% on the fabric, which can be calculated from Table 7-2.

BP2 had 50% of Bi$_2$O$_3$ in its coating material, while BP3 had 66.6% of Bi$_2$O$_3$. Although BP3 was coated with a high concentration of Bi$_2$O$_3$ as compared to BP2, BP3 allowed 17% of X-ray transmittance, similar to BP2. This is because BP2 and BP3 had similar amounts of Bi$_2$O$_3$ on the fabric (Table 7-2). It was also noted that BP2 and BP3 achieved the same X-ray shielding levels when compared to the Regular Lead sample tested (Figure 7-1). BP2 had 1136.7 g/m$^2$ of Bi$_2$O$_3$ while BP3 had 1219.6 g/m$^2$. However, the overall coated fabric weight of BP2 was higher than that of BP3 due to different amounts of PVC coatings. In other words, the reduced X-ray transmittance was primarily due to increasing Bi$_2$O$_3$ and, to a lesser extent, the PVC concentration.

It can be seen from Figure 7-4 that the PVC resin has a low level of X-ray protection. Even when the polyester fabric was coated with 2753 g/m$^2$ PVC resin, the coated fabric could only block about 16% of X-rays.

Figure 7-4 Effect of amount of PVC resin coated on polyester fabric on X-ray transmittance (the error bars indicate one standard deviation)
BP4 was found to have more radiation-shielding ability with only 8% of X-rays transmitted, which is better than the benchmark lead-equivalent samples. Compared with the Regular Lead sample, the X-rays transmitted by BP4 decreased by nearly 50%. BP4 had 1837 g/m² of Bi₂O₃ with a total weight gain of 1848% when compared to the untreated polyester fabric. When compared to the BP3 sample, BP4 had a 34% increase in Bi₂O₃ on the weight of fabric; hence BP4 gave better X-ray protection.

From the above results and discussion, it can be concluded that a higher concentration of Bi₂O₃ coating material has a significant effect on X-ray shielding. The major contributor to X-ray shielding was Bi₂O₃. The PVC resin also showed some effect on the shielding ability, as shown in Figure 7-4. Some coated polyester samples showed similar attenuation when compared to the lead standard sheets. In contrast, the coated nylon samples showed lower X-ray absorption due to a smaller amount of Bi₂O₃ coating when compared to the polyester fabrics. This study used micro particles of Bi₂O₃ in 10 micron-metres. It has gone beyond the claims in relation to particle size of Nambiar et al. [103] and has demonstrated that even micro Bi₂O₃ particles in a suitable PVC resin matrix can also provide adequate X-ray shielding compared to lead.

7.3.1.2 Mass per unit area

The weights of the control lead samples were 2159 g/m² for Lite Lead and 2534.6 g/m² for Regular Lead. The weight of the nylon fabric before coating was 315.4 g/m², which is heavier when compared to the polyester fabric, which was 149.2 g/m². In order to reduce the weight of the coated samples, coated polyester fabrics were mainly studied.

BN1 and BN2 achieved a mass of 1392 g/m² and 2314 g/m² respectively, or a weight gain of 342% and 634% respectively, when compared to uncoated nylon (Table 7-2). BN2 had similar weight to the Lite Lead sample but showed poor X-ray shielding capability. Hence, lightweight fabrics and high concentrations of Bi₂O₃ should be used for the material development.

BP4 was heavier than the lead samples and the heaviest fabric among all the coated samples. BP2 had similar weight to Regular Lead and showed similar X-ray shielding performance when compared to the lead samples. BP1 and BP3 showed 1223% and 1227% weight gain, respectively. Although BP1 and BP3 were similar in weight, BP3 achieved the same level of shielding for X-rays as Regular Lead, whereas BP1 did not
show a matching level of X-ray shielding due to a reduced amount of bismuth in the coating. Overall, this study demonstrates that selected Bi$_2$O$_3$-coated fabrics can match the weight and X-ray shielding performance of lead samples.

7.3.1.3 Material thickness

The level of X-ray penetration is expressed as the function of the amount of radiation that successfully passes through an object. In assessing this, attenuation is the inverse of penetration, and the level of the latter depends on the energy in the photons and the attributes of the object itself [121]. Thickness is thus an important feature of radiation protection and an apron must be thick enough, in addition to other qualities, to prevent penetration of ionising radiation [3]. For example, when 1.00 mm of lead will provide more than 99% protection, 0.01 mm will provide about 25% [5].

Table 7-3 shows the thicknesses of the uncoated and coated samples, including the reference lead sheets. The nylon uncoated fabric used for this study had a thickness of 0.59 mm, while the uncoated polyester fabric had a thickness of 0.18 mm. The lead samples had thicknesses of 0.53 mm for the Lite Lead sheet and 0.66 mm for the Regular Lead sheet.

Table 7-3 Material thickness of uncoated fabrics, coated fabrics and lead samples

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Initial thickness (mm)</th>
<th>Final thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BN1</td>
<td>0.59</td>
<td>1.03</td>
</tr>
<tr>
<td>BN2</td>
<td>0.59</td>
<td>1.47</td>
</tr>
<tr>
<td>BP1</td>
<td>0.18</td>
<td>1.04</td>
</tr>
<tr>
<td>BP2</td>
<td>0.18</td>
<td>1.27</td>
</tr>
<tr>
<td>BP3</td>
<td>0.18</td>
<td>1.04</td>
</tr>
<tr>
<td>BP4</td>
<td>0.18</td>
<td>1.33</td>
</tr>
<tr>
<td>Lite Lead</td>
<td>–</td>
<td>0.53</td>
</tr>
<tr>
<td>Regular Lead</td>
<td>–</td>
<td>0.66</td>
</tr>
</tbody>
</table>

All of the coated samples were thicker than the lead samples. The nylon-coated samples BN1 and BN2 showed thicknesses of 1.03 mm and 1.47 mm respectively and, when compared to the rest of the samples, BN2 was the thickest. However, while BN2 was thicker than the other samples, its X-ray shielding capacity was not relatively higher. In this context, it implies that although thickness plays a role in X-ray attenuation, the
primary contributor is the amount of Bi$_2$O$_3$ coated onto the textile materials. Manual assessment of fabric flexibility suggested that all coated fabrics had less bending force due to the PVC resin than the lead sheets. Since fabric thickness affects flexibility, a high Bi$_2$O$_3$ concentration in coating formulations is preferred.

When comparing the polyester-coated fabrics, BP1 and BP3 showed a similar thickness (1.04 mm); however, BP3 showed better X-ray shielding due to a higher concentration of Bi$_2$O$_3$. Samples BP2 and BP4 achieved 1.27 mm and 1.33 mm thicknesses with percentage increases in coating thickness of 606% and 641%, respectively. The resulting thickness was due to the high amount of Bi$_2$O$_3$ applied.

### 7.3.1.4 Morphological structures of the fabrics

From Figure 7-5, it is evident that particles were present in the lead samples and particle size was at the micron level. It appears that on the surface of the Regular Lead sample, there were more pronounced particles in a given area when compared to the Lite Lead sample. This may imply that the size and number of particles on the surface affect X-ray attenuation. Furthermore, the increase in the weight of the Regular Lead sample is an attribute of the quantity of lead particles in the sample when compared to the Lite Lead sample.
Figure 7-5 (a) and (b) SEM images of lead samples, surface view; (c) and (d) SEM cross-section images for lead samples.

Figure 7-6 shows SEM images of the nylon and polyester samples coated with Bi$_2$O$_3$. It can be seen from the figure that the uncoated fabrics had a plain-weave structure. The coating was on one side of the fabric and primarily on the surface of the fabric. The uncoated fabric side could be exposed as the surface of an apron. This would save half the weight of casing material for an apron.

The mixed PVC and Bi$_2$O$_3$ coatings were homogeneously spread on the coating side of the fabric surfaces. From the cross-section images in Figure 7-6, it can be seen that the coatings also penetrated into the structure of the BN1 and BP1 fabrics, which would result in a durable coating. Similar observations were noted for the other coated samples. The surface of sample BN1 shows fewer Bi$_2$O$_3$ particles in a given area compared to BP1 because the coating formulation for BP1 contained a much higher amount of Bi$_2$O$_3$ than for BN1 (Table 7-3). For effective radiation shielding and coated fabric weight reduction, a high concentration of Bi$_2$O$_3$ in the coating formulation should
be considered. This research has demonstrated that Bi$_2$O$_3$ is a suitable alternative to lead. The real advantage of using Bi$_2$O$_3$ is that it is not classified as a dangerous substance, because it has a much lower level of toxicity compared to lead.

Figure 7-6 SEM images of the uncoated and coated fabrics, as well as cross-sections of the coated nylon and polyester samples.
7.3.2 Evaluation of X-ray radiation shielding performance of barium sulphate-coated fabrics

7.3.2.1 Coating methods

The fabric samples were coated using two chemical components made up of three different application levels of BaSO₄ only, a combination of BaSO₄ and bismuth oxide (Bi₂O₃), and a combination of BaSO₄ and Bi₂O₃ with PVC resin using a knife-edge with roller on a Mathis coating machine. Details of the coating are shown in Table 7-4. For example, to prepare sample BSN1, 100 g of PVC resin and 20 g of BaSO₄ were mixed in a blender for 15 min. to become consistent. The mixture was then coated on the fabrics using a prescribed amount of coating for each sample. Three different samples were coated using the formulation developed, and the fabrics were then pre-dried at 60 °C and further cured at 150 °C in an oven for 5 min. By the same method, PVC only was coated in a prescribed amount on each sample, then pre-dried at 60 °C and further cured at 150 °C in an oven for 5 min.

Table 7-4 Coating description (BS = BaSO₄; N = Nylon 6.6; BO = Bi₂O₃; PVC = polyvinylchloride)

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Coating formula (g)</th>
<th>%BS in coating material</th>
<th>%BO in coating material</th>
<th>%PVC in coating material</th>
<th>Weight of coated fabric (g/m²)</th>
<th>Weight of BS on fabric (g/m²)</th>
<th>Weight of BO on fabric (g/m²)</th>
<th>Weight of barium on fabric (g/m²)</th>
<th>Weight of bismuth on fabric (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSN1</td>
<td>100 PVC + 20 BS</td>
<td>16.7</td>
<td>0</td>
<td>83.3</td>
<td>2321.5</td>
<td>334.22</td>
<td>0</td>
<td>196.66</td>
<td>0</td>
</tr>
<tr>
<td>BSN2</td>
<td>100 PVC + 50 BS</td>
<td>33.3</td>
<td>0</td>
<td>66.7</td>
<td>2321.4</td>
<td>668.40</td>
<td>0</td>
<td>393.29</td>
<td>0</td>
</tr>
<tr>
<td>BSON</td>
<td>100 PVC + 20 BO + 30 BS</td>
<td>20</td>
<td>13.3</td>
<td>66.7</td>
<td>2321.8</td>
<td>401.3</td>
<td>267.5</td>
<td>236.12</td>
<td>239.95</td>
</tr>
</tbody>
</table>

Note: the 'weight of BS and BO on fabric' was calculated by assuming no weight changes before or after PVC curing (weight of nylon base fabric = 315.4 g/m²).

7.3.2.2 X-ray protection performance

Figure 7-7 compares the results for X-ray radiation shielding. The transmittance value corresponds to the amount of X-ray that penetrated through the coated samples, and shows the shielding efficiency of the barium and bismuth elements. Initial exposure was measured without any fabric and was then taken into consideration as the control. The
nylon (N) fabric without any treatment was also measured as a reference for comparing against the coated samples. From Figure 7-7, it can be seen that the uncoated control nylon fabric was less effective. It allowed the greatest transmittance of the X-rays with a value of 96.7%. The transmittance values for Lite Lead (LL) and Regular Lead (RL) were about 18% and 17%, respectively. These values are typical for standard lead-equivalent (mm Pb) protective aprons. These transmittance values were then used as a benchmark for comparing the coated nylon fabric samples.

![Figure 7-7 Comparison of the percentage of X-rays transmitted (%) of control (air), uncoated nylon 6.6 fabric (N), standard lead samples (LL & RL) and coated samples against the weight of BaSO₄ and Bi₂O₃](image)

From these results, it can be concluded that sample BSN1 with 2006.1 g/m² of coating material applied achieved 84.5% transmittance, which shows that the coated fabric was less effective as a radiation-shielding material due to the insufficient amount of BaSO₄ on the fabric. Clearly, 334.2 g/m² of BaSO₄ is not enough to absorb the high energy of X-ray radiation. When the quantity of BaSO₄ was increased to 668.4 g/m² for sample BSN2, the radiation-absorbing ability moderately improved by around 16.5%. Sample BSN2 indicated 70.5% transmittance of X-rays. In comparison to the lead standard samples LL and RL, the BaSO₄-coated fabrics were ineffective as radiation-shielding materials. A possible explanation for these poor results may be related to the lower atomic number of barium in comparison to lead, which is Z=82, its density of 11.34 g/cm³ as well as lead’s atomic mass number of 207.2 AMU.
As shown in Figure 7-7, the mixture of BaSO$_4$ and Bi$_2$O$_3$ in sample BSON had better shielding ability than the fabrics coated with BaSO$_4$ only. BSON with a similar amount of coating as BSN2 (Table 7-4) showed 55.6% X-ray transmittance. The improvement was due to the fact that instead of BaSO$_4$, 267.5 g/m$^2$ of Bi$_2$O$_3$ was applied onto the fabric, and that bismuth has a high atomic number ($Z$=83), high density (9.8 g/cm$^3$) and a high atomic mass number (208.98 AMU) as compared to barium. X-ray attenuation depends on the energy of the X-ray beam, the electron density of the attenuating materials, and also the atomic number and electron-binding energy of the attenuating materials. Generally, materials with high atomic numbers have higher binding energies. More X-ray absorption occurs in these materials. For compound materials, the effective atomic numbers are considered. Hence, BaSO$_4$ and Bi$_2$O$_3$ should perform much better than PVC in terms of X-ray protection.

Figure 7-8 shows the effects of different concentrations of PVC, similar to the weight effects shown in Figure 7-4. It confirms that PVC has an effect in reducing the transmittance, although it is not as significant as BaSO$_4$ and Bi$_2$O$_3$. For example, the sample with 2265 g/m$^2$ pure PVC resin reduced the transmittance of X-ray to 83%. This indicates that the main attenuation of X-ray was from the metals barium and bismuth, and to a lesser extent from the PVC. When in comparison with the lead standard reference, the BSON sample fell short with 18% transmittance. The small error bars in Figure 7-7 and Figure 7-8 suggest that the difference in attenuation of X-rays between samples is significant. Hence, the coated fabrics cannot be used as standard X-ray shielding garments. For improvement, metals with high atomic numbers, high density and high molar mass should be considered, as these properties have direct correlation with the X-ray attenuation coefficients.
Several reasons for the poor effectiveness of the coated samples may be summed up. First, the insufficient amounts of BaSO_4 and Bi_2O_3 affected the results obtained. Even though the PVC resin showed some effect on shielding ability, as shown in Figure 7-8, a higher concentration of coating material will have a more significant effect on X-ray shielding according to Maghrabi et al. [63] when it mentions in relation to Figure 7-4 that the weight of PVC has an effect but the main input comes from the metal. Despite this, the major contributors to X-ray shielding were BaSO_4 and Bi_2O_3. However, a high concentration (e.g. 350g to 500g) of BaSO_4 had an impact on the weight of sheets made with it [111].

Secondly, the amount of barium in BaSO_4 is 58.9% by weight, whereas the amount of bismuth in Bi_2O_3 is 89%. Hence, Bi_2O_3 is a better X-ray absorber than BaSO_4. One of the aims of this chapter was to investigate the shielding performance of BaSO_4 alone and its mixture with Bi_2O_3 in considering BaSO_4 as a non-toxic chemical. In this experiment, it was also imperative to achieve a minimum weight by reducing the weight of chemical concentration used and the amount of coating material applied.

Moreover, several studies have reported that the size of metal particles has an impact on X-ray attenuation [103, 105]. Comparing this study with other studies such as that of Kim et al. [111], which only used BaSO_4 with a particle size of 0.03–0.05 μm for barium sheets, it can be seen that this study has used large particle sizes starting from ~1 μm. This shows that micro-particles in a suitable PVC resin matrix and at a reasonable
concentration can provide adequate X-ray shielding. These findings enhance understanding of the important correlation between the metal elements and the required concentration of chemicals, which have direct effects on X-ray attenuation coefficients.

7.3.2.3 Mass per unit area and material thickness

It can be seen from the data in Table 7-5 that the uncoated nylon fabric had a fabric weight of 315.4 g/m². For comparison, all coated nylon fabric samples, BSN1, BSN2 and BSON, had similar weights, i.e. 2321.5, 2321.4 and 2321.8 g/m², respectively, as the same prescribed amount of coating material was applied to each sample. The BSN1 sample was applied with 334.22 g/m² of BaSO₄ with PVC resin, while the BSN2 sample received a double concentration of BaSO₄ (668.40 g/m²). In comparison, the BSON sample had 401.3 g/m² BaSO₄ and 267.5 g/m² Bi₂O₃ applied on the fabric sample. All three samples BSN1, BSN2 and BSON showed a weight gain of 636%, as seen in Table 7-5. In contrast, all coated samples had the same weight but their absorption efficiency for X-ray was very different. The highest X-ray transmittance was with BSN1, whereas the lowest transmittance was with the coated sample BSON. This again suggests that the metal concentration used for coating affects the X-ray shielding capacity.

Finally, the X-ray attenuation for all coated samples was lower than for the lead reference samples. Despite heavy coating, the ability of BSN1, BSN2 and BSON to absorb X-rays was still insufficient. The proportion of metals should be increased for effective X-ray protection. It is noted that the lead standard sample weight was measured as 2159 g/m² for Lite Lead and 2534.6 g/m² for the Regular Lead sample, which is slightly higher than their specifications.

Table 7-5 Mass per unit area of uncoated fabric, coated samples and standard lead samples

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Uncoated fabric weight (g/m²)</th>
<th>Final fabric weight (g/m²)</th>
<th>Weight difference (g/m²)</th>
<th>Add-on weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lite Lead (LL)</td>
<td>–</td>
<td>2159.0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Regular Lead (RL)</td>
<td>–</td>
<td>2534.6</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>BSN1</td>
<td>315.4</td>
<td>2321.5</td>
<td>2006.1</td>
<td>636.0</td>
</tr>
<tr>
<td>BSN2</td>
<td>315.4</td>
<td>2321.4</td>
<td>2006.0</td>
<td>636.0</td>
</tr>
<tr>
<td>BSON</td>
<td>315.4</td>
<td>2321.8</td>
<td>2006.4</td>
<td>636.1</td>
</tr>
</tbody>
</table>
As shown in Figure 7-9, the standard Lite Lead sample was thinnest at 0.53 mm. The Regular Lead sample was 0.78 mm in thickness. The thickness of the uncoated nylon fabric sample was between those of LL and RL. The coated nylon samples, BSN1, BSN2 and BSON, had a similar thickness, 1.46 mm, because all had the same amount of coating applied using a fixed thickness gauge. The coating increased the thickness by 147%. Even though all coated fabric samples were thicker than the standard lead reference, their shielding ability could not match those of the lead samples due to the low concentrations of barium and bismuth used.

In physics, linear attenuation coefficients (μ) can be described as the thickness of shielding material which influences the level of attenuation. Thickness is a significant factor in X-ray attenuation; the thicker the material, the increased distance of travel of the X-ray, and hence the greater the thickness of the attenuating material, the greater the attenuation [23]. Although thickness plays an important role in X-ray attenuation, the major contributor is the metal element’s atomic number, density, atomic mass number and proportion. The X-ray penetrating ability is inversely proportional to the atomic number. Hence, it is important to choose the right metal.
7.3.2.4 Morphological structures of the fabrics

Figure 7-10 shows the surface of the woven nylon 6.6 untreated fabric, featuring small openings and uneven surfaces. The cross-section for the coated sample BSN1 indicates that the coating has effectively covered the fabric surface, formed a shielding layer and filled in the spaces, pores and interstices of the fibre bundles. It is apparent that the coating penetrated into the structure of the BSN1 fabric, which resulted in a durable coating. The X-ray shielding powders of barium and bismuth show good distribution in the PVC resin. Similar observations are noted for the other coated samples. The uncoated fabric side could be exposed as the surface of an apron. This would save half the weight of casing material for an apron.
It can be seen in Figure 7-10 that the distribution of barium particles in the PVC matrix for the BaSO₄ / Bi₂O₃ sample is even and the particle size is at the micron level. It appears that on the surface of the BSN2 and BSON samples there are more large-sized particles in a given area when compared to the BSN1 sample. This implies that the size and number of particles on the surface affect X-ray attenuation. The surface images show that the coating is on top of the fabric and primarily on the surface of the fabric. The
mixture of PVC and the BaSO\(_4\) and Bi\(_2\)O\(_3\) coating is homogeneously spread on the coating side of the fabric surface. This finding agrees with the report of Lin et al. [118], which showed that a good combination of selective X-ray shielding powder with particle size under 500 μm mixed with urethane resin provided good X-ray shielding.

For improving radiation shielding and reducing coated fabric weight, high concentrations of BaSO\(_4\) and Bi\(_2\)O\(_3\) in the coating formulation should be considered. This research has demonstrated that a combination of BaSO\(_4\) and Bi\(_2\)O\(_3\) could be a suitable alternative for lead. The real advantage of using BaSO\(_4\) and Bi\(_2\)O\(_3\) is that they are not classified as dangerous substances, because they have much lower levels of toxicity as compared to lead.

### 7.3.2.5 Total mass attenuation coefficient

The theoretical total mass attenuation coefficients (\(\mu/\rho\)) at different energy levels between 0 and 105 MeV were calculated for mixtures of different proportional weights of BaSO\(_4\), Bi\(_2\)O\(_3\) and PVC, and compared to those of pure lead and PVC using WinXCom computer software. The results are shown in Figure 7-11.

![Figure 7-11 XCOM simulations of pure lead, pure PVC, BSN1, BSN2 and BSON](image)
The theoretical attenuation coefficients associated with different coating materials were in agreement with the X-ray transmittance values experimentally obtained. As anticipated, all coated fabrics exhibited weaker attenuation performance than lead; however, replacing BaSO₄ with some Bi₂O₃ led to higher X-ray attenuation performance than BaSO₄ alone over the designated energy range (between 0 and 105 MeV). The appearance of three major absorption edges (2.6E-03 MeV, 1.3E-02 MeV and 8.8E-02 MeV) in the BSON XCOM spectra showed more attenuating activity at low energy (below 1 MeV) X-ray radiation, as compared to PVC with only one major adsorption edge at 2.8E-03 MeV, BSN1 with two edges (3.0E-03 MeV and 3.7E-02 MeV) and BSN2 with two major edges (2.8E-03 MeV and 3.7E-02 MeV). According to the WinXCom results, the overall mass attenuation coefficients associated with the energy range and coating chemicals used are in this order: lead > BSON > BSN1 > PVC.

7.3.3 Antimony pentoxide coating on knitted fabrics for X-ray shielding

7.3.3.1 Coating method

The nylon/wool fabric samples were coated using five different application levels of Sb₂O₅ and Bi₂O₃, PVC resin and Plre-9000, as shown in Table 7-6. The coating formulation was designed to reduce the viscosity of the PVC to an acceptable viscosity level of 3000 cps suitable for the Mathis laboratory coating device and knife-edge coater. For example, 100 g of Bi₂O₃, 100 g of Sb₂O₅, 100 g of PVC resin and 60 ml of Plre-9000 were mixed in a blender for 15 min. to become consistent; the mixture was then coated on fabric. Five different samples were coated using the formulation and then dried at 60 °C and further cured at 150 °C in an oven for 10 min. The calculation was done by taking the weight of fabric before and after coating. The weight of coating on the fabric was calculated assuming no weight changes before and after curing.
7.3.3.2 X-ray shielding performance

Assessments of samples before abrasion test, Initial exposure was measured without any sample, achieving 1.18 mGy transmitted dose and a dose rate of 36.7 mGy/s. This was considered the air control. The uncoated fabric KN was also measured as a reference to compare with the coated samples. As expected, KN fabric showed poor dose reduction (0.8%), transmitting 1.17 mGy of the applied dose. It is worth noting that the X-ray dose for all samples was 1.18 mGy.

Data in Figure 7-12 represents the shielding performance for all experimental samples before applying any damage to the samples. The transmittance value corresponds with the proportion of X-rays that penetrated through the coated fabric and indicates the shielding effectiveness based on the characteristics of the X-ray absorber. Dose reductions through shielding are presented as percentages (%). A higher transmittance value corresponds to lower X-ray absorption, meaning that the sample is less effective for radiation protection; a lower transmittance value corresponds to high X-ray dose absorption. LL and RL represent the benchmark for this study, which is the lead material. As we can see, LL and RL achieved 86% and 87% dose reduction, indicating excellent shielding performance against X-ray radiation.
Sample KBS2 showed 79.6% dose reduction. The low concentrations of Bi₂O₃ (709 g/m²) and Sb₂O₅ (709 g/m²) were insufficient to absorb all the X-ray energy transmitted. The Sb absorber has a lower atomic number (51); however, Sb has a wide atomic cross-section with 145 pm, where Bi has a wider atomic cross-section of 160 pm. When an element has a larger atomic cross-section, it means more absorption of X-ray photon energy that penetrates the material [122]. Furthermore, samples KBS3 and KBS4 attained results of dose reduction of 74.3% and 72.3%, respectively, despite Sb₂O₅ concentrations being different for each sample. For example, the weight of Sb inside sample KBS3 was 598 g/m², and sample KBS4 had a concentration of 370 g/m² of Sb, this dissimilar weight of Sb plus Bi₂O₃ had an effect on the results achieved by only decreasing the transmission by 2%. It should be kept in consideration that antimony has a lower atomic number and less density, which can have a significant impact on X-ray absorption (see Table 7-1).

Sample KB1 was found to have a significant shielding effect similar to LL with 86.1%. The reason for this positive outcome is due to the concentration of Bi₂O₃ of 55.5% in the coating material, meaning the coverage weight of Bi₂O₃ was 1366 g/m². In a similar study by Maghrabi et al. [63], a coating of only 219.6 g/m² Bi₂O₃ on woven fabric showed a parallel attenuation level to the lead standard for X-ray absorption. In Table 7-1 it can be seen that the oxygen mass represents 10.3% in Bi₂O₃ and the added weight does not contribute significantly to the attenuation capabilities of the materials. Nonetheless, the high percentage of Bi metal at 89.6% suggested that this material is worthy of
investigation. Also, the importance of understanding the cross section for the elements is that when the element has larger atomic cross section, it means more absorption of X-ray photon energy that penetrates the material [123].

KS5 obtained only 69.6% dose reduction, which means that this sample may not be suitable for X-ray shielding garments since this sample transmitted about 30% of X-rays, where the standard transmission level for RL and LL transmitted only 14% and 12.7% respectively. The KS5 sample was coated with Sb₂O₅ at an amount of 55.5%. In comparison, sample KB1 had a similar amount of concentration (55.5% of Bi₂O₃), but the results were different because Sb has a low atomic number (51) and low density of 6.69 g/cm³ (as shown in Table 7-1), and the Sb concentration (1418 g/cm²) was not high enough to absorb the bulk of X-ray photons. McCaffrey et al. [2] reported that radiation-shielding materials investigated in their experiment were three low-Z/high-Z bilayer materials with approximate weights of Sb 70%/W 30%, Sb 40%/Bi 60% and Ba 60%/Bi 40% and utilised six X-ray qualities in the energy range 50–150 keV. The ordering of the metal bilayers low-Z to high-Z provided up to five times more attenuation per unit mass than Pb-only garments. The available Sb/Bi and Sb/W bilayers offered substantial reductions in weight over Pb-based materials for equivalent attenuation, but the reductions varied with X-ray energy. The overall knowledge gained from this experiment was that Sb could be used independently, or in mixture with high Sb concentration.

7.3.3.2.1 Assessments of samples after abrasion test

It can be seen from Figure 7-13 that abrasion changed the results of dose reduction significantly depending on the level of abrasion on the coated samples. The LL and RL samples showed good resistance to abrasion, and the coated samples showed steady decline in shielding efficacy with an increase of the abrasion cycles. After 1000 rubs, the samples KB1, KBS2, KBS3 and KBS4 reduced their shielding performance by 2%, and sample KS5 showed less than 2% of dose reduction. As the abrasion continued, all samples lost more shielding performance. After 10 000 rubs, all coated samples declined dramatically to 57.7% ~ 65.3% dose reduction, indicating they could not be used for X-ray shielding purposes any more. For example, KB1 had a dose reduction of 65.3%; the other samples of KBS2, KBS3, and KBS4 also showed significant decreases in shielding efficiency. Furthermore, the sample KS5 displayed 59.2% at 10 000 abrasion cycles. Although it is considered to be less affected by abrasion at the same level compared to
the other samples, KS5 had poor shielding performance before abrasion. The reduction in radiation shielding of the coated samples due to abrasion suggests that future investigation for the development of durable coated fabrics is required.

Figure 7-13 X-ray shielding performance of all experimental samples after abrasion damage

Figure 7-14 shows the dose reduction after the stretch and recovery treatment. It can be seen that all samples showed similar X-ray shielding performance before and after stretching. For the coated samples, the difference in dose reduction between stretching in the wales direction and the course direction was generally small. KBS2 in the wales direction had a dose reduction of 77% while the course achieved 72%. With samples KBS3, KBS4 and KS5, the wales direction indicated a lower dose reduction than the course direction. This may be because of coating unevenness due to the knitted fabric structure, which varied the stretching and recovery properties. On the other hand, the lead benchmark showed no significant reduction due to the smooth sheeting of PVC resin, which made the lead samples more elastic.
7.3.3.3 Physical and mechanical performance

Figure 7-15 shows the morphology of uncoated and coated sample KS5. Figure 7-15 (a, b) shows the fabric surfaces of the knitted nylon plated with wool. The structure of the uncoated fabric is open and its surfaces are uneven. After coating, the pores within the KS5 fabric structure were filled with coating material and the fabric surfaces became smooth; see Figure 7-15 (c, d). The coated fabric showed good resistance to abrasion with no significant surface changes after applying 1000, 2500 and 5000 rubs, as shown in Figure 7-15 (e, f, g, h, i, j). However, samples abraded at 7500 and 10 000 cycles began to show signs of wear on the rubbed surface (Figure 7-15 (k, l, m, n)). Regardless, the cross-section view of the coated fabric after 10 000 cycles of abrasion (Figure 7-15(o, p)) shows good durability, with the coating materials firmly adhering to the fabric. This observation suggests that this coating method could be applied for future research.
7.3.3.3.1 Stiffness of samples

The weight and thickness of fabric are usually used as standard indicators for the comfort level [56]. They can also play a significant role in the X-ray shielding capacity and protection[121]. However, the results were not very encouraging for the developed coated samples in term of weight and thickness due to the heavy weight of the backing textile, KN; however, the lead benchmark has gone through processes and manufacturing treatments for the optimum thickness and weight.

Flexural rigidity is related to the quality of stiffness that can be appreciated when a fabric is handled. Cloth with high flexural rigidity tends to feel stiffer. Figure 7-16 shows
that the uncoated KN had the lowest flexural rigidity, 279 $\mu$N.m, and coating on the fabric increased the flexural rigidity of the coated sample. On the other hand, the LL and RL sheets had very high flexural rigidity. Hence, the super flexibility of the coated fabric is a significant advantage as compared to the LL and RL sheets.

![Graph showing flexural rigidity (G) versus weight (g/m²) for all experimental samples](image)

Figure 7-16 Flexural rigidity (G) versus weight (g/m²) for all experimental samples

It can be seen from Figure 7-16 that the uncoated fabric, KN, was a medium-weight fabric at 474 g/m². Furthermore, all the developed coated samples were heavier than the lead standard samples. Their weight was 2159 g/m² for LL and 2535 g/m² for RL.

The thickness of the uncoated fabric was 1.3 mm, which means that it was thicker than the lead sheet samples, LL and RL, which were about 0.5 mm, as shown in Figure 7-17. The thickness of the coated samples ranged from 2.1 mm to 3.1 mm. The sample KS5 was the heaviest and thickest coated sample among all the developed samples, with 3864 g/m² and 3.1 mm. Due to its high weight, thickness and flexural rigidity, as well as its poor radiation-shielding effect, the coating formulation for KS5 is not recommended.

Material thickness is an important feature in radiation protection. It is imperative that a medical apron should be thick enough to prevent penetration of ionising radiation [3]. Furthermore, most of the observed data in Figure 7-14 for samples KBS2, KBS3, KBS4 and KBS5 indicates they did not achieve the shielding requirement threshold, which is 84.58%. KB1 was the only sample with the minimum shielding capacity, although this
sample had similar thickness to sample KBS2, 2.1 mm. KB1 indicated a weight of 2931 g/m², similar to that of the RL sample and a weight increase of 519% over the uncoated sample. Sample KB2 had a weight increase of 593% and actual weight of 3026 g/m². Although thickness plays a significant role in X-ray attenuation, the primary contributor is metal concentration. It is worth noting that according to previous studies, the PVC resin used also showed some X-ray shielding protection; however, the significant influence was seen with a considerable amount of PVC on fabrics at least above 2800 g/m² [63]. The main contribution to X-ray shielding performance comes mainly from the high atomic number and density and cross-section of the metal element used.

![Graph](image)

Figure 7-17 Bending modulus (q) versus thickness for all experimental samples

An important issue with current lead aprons is their vulnerability to developing cracks, rips, holes, and tears due to the inflexibility of the lead sheets. Consequently, these defects can reduce the shielding efficiency and allow leakage of X-ray radiation [7],[68].

Figure 7-16 and Figure 7-17 illustrate that most of the sample fabrics – KB1, KBS2, KBS3 and KBS4 – indicate low flexural rigidity, ranging from 40 mN.m to 74 mN.m, and low bending modulus, ranging between 22 mN/m² and 330 mN/m², in comparison with the standard lead sheet, LL 692 mN.m (G), 166 mN/m² (q), and RL 780 mN.m (G), 133 mN/m² (q). These findings are in agreement with studies showing that lead sheets are stiffer and have poor flexibility [7].
7.3.3.3.2 Abrasion resistance of experiment samples

The abrasion resistance and mass loss of the coated fabrics, the uncoated sample and the lead benchmarks were determined by using a Martindale tester after 1000, 2500, 5000, 7500 and 10 000 rubbing cycles. The results are shown in Figure 7-18. Abrasion resistance varied across five different levels of abrasion tests. The sample KN had high resistance to abrasion. Hence, KN is a suitable substrate in terms of resistance to abrasion. The LL and RL samples showed good resistance to abrasion and had zero mass loss in the 1000 and 2500 abrasion cycles. They began to lose mass slightly at 5000 cycles. At 10 000 abrasion cycles, there was a noticeable loss of mass. Removing the X-ray absorbing particles from the tested samples means reducing the shielding effectiveness.

Results in Figure 7-18 also show that abrasion caused significant loss of mass for the coated fabrics. An increase in the number of abrasion cycles led to an increase in the amount of mass loss. Abrasion affected not only the integrity of the coated fabrics, but also the shielding performance of these coated samples. As seen in Figure 7-14, the decrease in shielding efficiency was due to the increase in the number of abrasion cycles. Similar findings have been reported on the mass loss of artificial leather backed by knitted fabric [46]. The lesson learned from this experiment is that the resin used has poor durability compared to the lead material, but is more flexible than the lead samples. This needs further investigation as the most durable and most flexible resin should be used for coating textile substrates.

![Figure 7-18 Abrasion resistance of experimental samples](image)
7.3.3.3 Stretch and recovery properties of coated samples

- **Stretchability**

The aim of this experiment was to observe the elasticity of the knitted coated fabrics, and how far the coated fabrics can be stretched at an extension force of 30 N without developing any cracks or breaks to the coated surfaces. Each sample was tested individually in both wales and course directions. As seen in Figure 7-19, the KN uncoated sample had much higher elongation in the course direction (54%) than in the wales direction (44%). The elasticity of the fabric was considerably reduced due to the coating materials. The coated samples KB1, KBS2 and KBS3 also demonstrated that the elongation in the course direction was higher than in the wales direction. This can be related to the engineering structure of the knitted fabric, which can be more easily stretched in the course direction than in the wales direction. This trend implies that the wales direction of the coated sample should be used to take the load for x-ray protective garments.

It was observed that all samples at 30 N force did not show any cracks or tears on the coated surfaces, indicating the coated samples had the expected durability. However, after each cycle the extension of the fabric increased gradually. Nevertheless, five stretch and recover cycles did not appear to have an effect on the coated samples’ shielding efficacy but only on the RL and LL benchmarks.

![Figure 7-19 Stretch properties of coated samples in both directions at 30N load and 5th cycle](image-url)
Figure 7-19 shows that the lead benchmark LL had elongation of 15% and RL had elongation of 14% at 30N load and 5th cycle. Unlike the knitted textile fabrics, the lead sheet benchmarks LL and RL are solid sheets and there is no specified direction. Hence, both LL and RL lead samples showed similar extension levels in both directions. The stretch properties could affect the shielding performance.

- **Recoverability**

The residual extension after 1 minute of relaxing on a flat surface can be seen in Figure 7-20. Although the fabric KN has very poor stretch recovery performance, all the coated samples showed lower residual extension than the lead benchmarks. It is advantageous if an apron has excellent recovery properties in both directions so as to maintain its original shape. The low residual extension of the coated samples suggests that the coated fabrics are better materials for aprons than lead sheets in terms of stretch and immediate recovery.

### 7.4 Conclusion

This research has demonstrated that Bi$_2$O$_3$, having a low level of toxicity hazard compared to lead, could be a suitable alternative for radiation-shielding. It has also
demonstrated that by coating fabrics with Bi$_2$O$_3$, the resultant fabrics can impart similar attenuation efficiency to that of regular lead aprons for X-ray protection. Coated polyester fabrics with higher concentrations (added-on weight 50% Bi$_2$O$_3$) showed enhanced shielding ability for X-rays. Although thickness played a significant role in X-ray attenuation, the primary contributor was the metal concentration. PVC resin also showed some shielding protection, but this was only seen with a significant amount of PVC on the fabrics. Nevertheless, for a 2753 g/m$^2$ PVC resin coating, the coated polyester fabric still could not block about 84% of X-rays.

This research has shown that micro-particles of Bi$_2$O$_3$ can be effective for X-ray attenuation. Choosing a lightweight fabric may be beneficial in contributing to a lower overall weight of the X-ray protective apron, in addition to accommodating a higher concentration of Bi$_2$O$_3$ in the coating formulation. Coating polyester fabrics with an added weight of around 1200 g/m$^2$ Bi$_2$O$_3$ gave a similar shielding ability to that of regular lead. This coated fabric could be produced to be 10% lighter than the commercial LL samples and 30% lighter than the commercial RL samples.

Knitted fabric samples have been coated with different combination of Sb$_2$O$_5$ and Bi$_2$O$_3$ as non-Pb materials. These coated samples were assessed and evaluated in term of X-ray shielding performance. It has been found that the sample KB1 was the only sample to present good shielding effects similar to the lead benchmark samples. On the other hand, all the coated samples failed to provide lighter weight and less thickness than the lead sheets due to the high application levels of PVC resin and Plre-9000 to bind the X-ray absorbers to the fabrics. Moreover, all the coated samples were investigated in terms of stiffness as clothing, with the findings suggesting that all had lower stiffness than the RL and LL standard sheets. The stretch and recovery results showed that the lead samples had poor recovery in comparison with the coated samples under 30 N load. When the number of abrasion cycles increased to 10,000 cycles, the X-ray shielding efficiency of all samples decreased. All coated samples had poor abrasion resistance and improvement in coated fabric abrasion resistance is recommended for future development.
Chapter 8: Conclusions and Future Research

8.1 Conclusions

Lead aprons have been used for almost a century to provide protection against X-ray radiation and they are still widely used for the same purpose. The current lead apron is associated with many problems, such as reduced effectiveness of protection and increased discomfort level. Defects in lead aprons such as cracks and holes can leak radiation and cause overexposure to individuals. All these common defects are well recognised by researchers. Similarly, poisoning from the lead material has prompted researchers to seek out alternative, less toxic materials. Additionally, lead aprons are heavy and uncomfortable to wear. The heavy weight is a cause of increasing musculoskeletal problems, including neck, shoulder and back pain in radiologists. Poor fitting of lead aprons has also been associated with increased incidence of breast cancer among female radiographers. These problems point to the need for further research and investigation into this type of protective clothing to assess its effectiveness in terms of shielding, comfort and garment design to suit the natural female curvature. The current thesis work has produced a light weight sample as alternative material to toxic lead sheets. This addressed the weight problem of X-ray aprons, but further weight reduction is necessary.

The lead sheets have very poor comfort characteristics, but excellent radiation-shielding ability. On the other hand, the fabric samples show poor absorption of X-ray radiation and therefore do not have any effective shielding ability. The abrasion resistance of the fabric samples in this study varied due to the weave structure and the end use of each sample. For instance, sample nylon wool (NW) has the highest resistance to abrasion, which means it is more durable than Kevlar wool (KW) and polyester cotton polyester cotton (PC). In term of comfort characteristics, the air permeability of all samples varies. Lite lead (LL) and regular lead (RL) show an expected zero mm/s liquid moisture spreading rate on their bottom surface due to their impermeability. In general, the highest results for air permeability are indicated by fabric samples polyester cotton, polyester, nylon wool and Kevlar wool. All six fabrics show good comfort properties, particularly in terms of moisture management. These fabrics could be used for apron casing to replace woven fabrics, which have poor comfort performance. Although all fabrics show enhanced comfort properties compared with lead sheets, the knitted fabric
plated with wool appears to be the best option among the fabrics studied to improve the comfort performance of the casing material and such fabric could be used as a substitute to hold the shielding absorber materials. The use of fabric garment as backing materials to the coating substances has many advantage like making the shielding more flexible and playable than the lead sheet. As a result, can be fit the female body structure more easily.

Lead aprons show high thermal and evaporative resistance due to the impermeable garment components and the thick layers within the aprons. All the selected commercial aprons were heavy, which would cause discomfort to the wearers, in particular for surgery and other medical procedures of long duration. A high level of stiffness was also observed in the lead aprons. The average air gap size at the chest, waist and hip regions was relatively high, indicating greater looseness in the lead aprons. Multiple pressure analysis revealed that the heavier weight aprons exhibited higher pressure loads to the shoulder areas. The thermal comfort, fit and weight distribution of these garments should be considered in future designs. The highly bulky of the lead sheet reduce their flexibility as a result can easily build crack and tears, which reduce the radiation shielding efficiency.

This work has developed unique basic designs of garments for protecting medical workers and patients in the future from radiation exposure. Based on analysis of female body measurements, this study presents alternative apron designs that, after being coating with absorber chemicals, could be worn by female medical workers. The three designs, namely, an open breast cup with round collar, front apron and maternity apron, are suited to the female body features, mainly the breast, waist and hip regions. The garment design is based on 3D scan measurements of the female body to put its features into perspective. As a result, the designed garments fit smoothly on female body curves in X-ray sensitive areas like the chest and abdomen, and on the entire body of female workers, since they are tailored to all the features of the female body. The design aspect is very important for this type of protective clothing. It takes into account the radio sensitive areas especially for women and how these areas can be fully covered for protection purposes. In addition, the fit on the body will not affect the body movement. The commercial lead aprons currently used are heavy and uncomfortable to wear, and lead itself is toxic. The use of X-ray radiation in diagnostic and therapeutic procedures has increased the need to develop new radiation-shielding aprons and clothing that are
both effective for protection and comfortable. This research has demonstrated that bismuth oxide (Bi$_2$O$_3$), having a low level of hazard compared to lead, is a suitable alternative. It has also demonstrated that lightweight fabrics can be produced by coating them with Bi$_2$O$_3$ and the resultant fabrics can impart similar attenuation efficiency to that of regular lead aprons for X-ray protection. Coated polyester fabrics with higher concentrations (added-on weight 50% Bi$_2$O$_3$) showed enhanced shielding ability for X-rays. Although thickness played a significant role in X-ray attenuation, the primary contributor was the metal concentration. PVC resin also showed some shielding protection, but only with a significant amount of PVC coating on the fabrics. Nevertheless, even for a 2753 g/m$^2$ PVC resin coating, the coated polyester fabric still could not block about 84% of X-rays.

This research has shown that micro-particles of Bi$_2$O$_3$ can be effective for X-ray attenuation. Choosing a lightweight fabric is likely to be beneficial in reducing the overall weight of the X-ray protective apron, in addition to accommodating a higher concentration of Bi$_2$O$_3$ in the coating formulation. Coating polyester fabrics with an added weight of around 1200 g/m$^2$ Bi$_2$O$_3$ gave a similar shielding ability to that of regular lead. This coated fabric could be 10% lighter than commercial Lite Lead and 30% lighter than commercial Regular Lead samples.

8.2 Scope and Limitations of Current Study

This thesis work has only studied micro-particles above 100 nm in size to produce the shielding effects. Nano-sized particles for X-ray protection should be evaluated as well. The machine used in this research for knitting the fabrics was a flat-bed machine of gauge E14, which is 14 needles/inch. The only way to obtain a very tightly knitted structure so that the coating could apply firmly to the surface of the fabric was by reducing the loop length. Knitting tight structures with very strong yarns like ballistic nylon is very difficult due to the limited stretch of these yarns. Tighter structures were not made so as not to break the machine needles. Only single jersey fabrics with a knitting transfer of 30 qualities (tightness) using 94 text of plated nylon wool were knitted. The fabric produced had high densities of 8.6 wales/cm and 6.2 courses/cm (fabric loop length was 6.63 mm).
8.3 Future Research

With the objective of expanding the knowledge of fabrics and coatings that could increase radiation-shielding efficiency and overall comfort, the effectiveness of the knitted fabric type of aprons has been positively evaluated. The use of viable processing methodologies for designing new garments with an advanced approach using microtechnology to enhance radiation shielding so as to meet the safety requirements for use in medical X-ray imaging facilities has succeeded.

However, only a limited amount of information has been obtained from this thesis work. This leaves a wide scope for further investigation. Therefore, some recommendations for future research are outlined as follows:

- Further research is needed to evaluate the serviceability and durability of fabrics coated with BaSO$_4$ and Bi$_2$O$_3$.

- There is an absolute need for further study into different methods of fabric coating, especially 3D printing, spray coating and coating on 3D shapes for female aprons.

- This research has found that fabrics of knitted structure are good for making designs in 3D shapes. However, their slightly heavy weight, which has resulted in the final outcome prototype, means that it is worth looking at different yarns with high strength, or even with X-ray absorbing function. This is a possible place for investigation for weight reduction.

- The dispersion of the micro-filler PVC mixing method was fairly homogeneous, although with some particle agglomerations, through the use of high-speed mixing. However, obtaining perfect dispersion of micro-fillers in polymer matrices is still challenging. Therefore, different ways of mixing as well as curing need to be investigated thoroughly in order to improve micro-filler dispersion.

- Further testing of the physical, mechanical and comfort properties, for example bending, tearing and abrasion testing of the coated fabrics, should be considered so that the fabrics can be used practically as X-ray shielding for long periods of time and their durability and comfort performance can be predicted.
The practical concentrations of barium and antimony in PVC should be increased to higher levels than the concentrations used in this study in order to provide even better X-ray attenuation properties and weight reduction. These two metal elements could be optimised and considered as candidates for effective X-ray shielding in diagnostic radiology.
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Appendices

Appendix 1:

Pressure maps of lead aprons
Appendix 2:

14 size female manikin and measurements were taken
Pregnant manikin and measurements were taken