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A Study of Shielding and Comfort Performance for Selected Fabrics Used as Casing Material for X-Ray Protective Aprons ⋆

Huda Ahmed Maghrabi [a,c], Lijing Wang [a,*], Pradip Deb [b], Arun Vijayan [a]

[a] *School of Fashion & Textiles, RMIT University, Brunswick, Victoria 3056, Australia*
[b] *School of Medical Sciences, RMIT University, Bundoora, Victoria 3083, Australia*
[c] *Department of Textiles and Clothing, Umm Al-Qura University, Mecca 24382, Saudi Arabia*

Abstract

Lead aprons are typically worn by radiographers to protect them from harmful radiation. As such, a good radiation shield must have a high Lead Equivalence to minimize the transmitted radiation dose during exposure. While most radiation shields fulfil this requirement by using matrices of lead and other substances, most aprons are uncomfortable to wear. Further, if the examination takes longer than expected, the radiographer will feel discomfort because of the heavy weight of the apron, or the smooth surface of the coated casing material. Another issue is the poor fit and design of the aprons due to the stiffness of the lead sheet. In general, the comfort characteristics of any textile material are related to air permeability, moisture management, abrasion resistance, fabric structure, thickness and weight, as well as yarn types. The objective of this study is to use standard testing methods to characterize some selected fabrics in terms of their X-ray shielding ability, physical, mechanical, and morphologic properties. The implication of this research will help for further study of this type of fabrics to improve thermal comfort of X-ray protective clothing.

Keywords: Lead Apron; X-Ray Shielding; Moisture Management; Fabric Comfort; Air Permeability; Abrasion Resistance

1 Introduction

Ionizing radiation has two main uses in human: to kill cancerous cells and to diagnose disease or injury [1]. X-ray is 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 [2]. To prevent unnecessary exposure to the radiologist and the patient, various protection measures have been standardized and are continually being improved [1].

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*Corresponding author.
Email address: lijing.wang@rmit.edu.au (Lijing Wang).

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Radiation shielding is categorized into biological and thermal shielding. Biological shielding is designed to reduce radiation to a safe and acceptable level for living organisms. The danger of exposure is further classified into external and internal categories [3]. External radiation emanates from an outside source and can only be reduced by providing a safe distance, a protective shield, and a time limit to the exposure. Internal radiation is a medical and hygiene problem and does not involve any external shielding.

Lead aprons are the most common type of personal shielding in radiology departments and the medical imaging industry, in general. Lead is an ideal material for radiation protection, but it compromises the comfort of the wearer [4]. The issue of comfort becomes even more important if the lead apron is worn for a long time. According to Van et al. [5], the most common comfort issue when selecting a lead apron is the weight of the apparel. Lead is a heavy metal, making a lead apron very heavy. Long-hour use of heavy aprons and apparel, especially in a catheterization laboratory or surgeries, can lead to discomfort, back pain, and the risk of permanent back problems. Modern technology has produced ultra-lite and light-weight aprons, but most are still heavy, and weigh about 3.8 kg [6].

Radiation shields are meant to be worn during radiological diagnostic/interventional procedures and/or oncological treatments. The shields are worn by clinicians, patients and physicians to selectively shield, isolate and protect parts of their body from radiation. The shields are reusable, meaning same shields may be used many times by different care providers and patients. For this reason, earlier shields were not finished to facilitate easy cleaning after use. These unsanitary shields may pose health risks to a person when they are used to cover parts of the body, especially the gonadal region. Adopting the hygienic use of the shields is one of the methods of tackling the problem [7, 8]. Hence, an apron casing is used for ease of cleaning.

Clothing insulation has a significant impact on thermal comfort, because it influences the heat loss and consequently the thermal balance. More layers of insulating clothing can avoid heat loss and help either keep an individual warm or lead to overheating. Medical protective clothing made of different materials should not induce any thermal discomfort. Such an uncomfortable sensation experienced by surgeons can decrease their psychomotor skills, and at the same time adversely influence the way an operation is carried out [9]. In this context, if a radiologist attempts to do examinations for more than 60 minutes, thermal discomfort becomes an issue and could negatively affect their performance, even though they usually perform procedures in an air-conditioned room. The heavy weight of the aprons and layers of clothing underneath, as well as the type of activities undertaken, all have an impact on the thermal comfort sensation.

It is generally agreed that thermal resistance, water-vapour resistance, moisture transfer, air permeability and surface friction are the most important parameters when choosing an apron [10, 11]. There are also other factors like size, fit and mobility of the wearer [12]. It is essential to consider these parameters when designing protective clothing. The attributes of an individual, the clothing and the environment influence comfort. Good personal apparel protection should be highly breathable. Breathability is the ability of a material to allow for the transmission of moisture vapour, or air, through it. The driving force of the moisture vapour is the level of humidity and heat on either side of the fabric, an attribute referred to as differential pressure. In the context of lead aprons, comfort without reducing the protectiveness of the material is critical [13].

This research investigates the comfort performance of a specific range of textile fabrics that could be used as alternative casing aprons. In ascertaining 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, or material used. These proposed alternatives should fulfil a balance between radiation protection and thermal comfort.

2 Experiment

All the fabric specimens were conditioned according to Australian Standard, AS 2001.1-1995, conditioning procedures, under 20±2 °C and 65±3% relative humidity for at least 24 hours before testing.

2.1 Materials

The specifications of all materials are shown in Table 1. Two lead equivalent samples were used as the benchmark for comparison. A regular lead equivalency sheet made from rubber, polyvinyl chloride and lead powder, weighting 2.4 kg/m^2 was used as inner layers. Similarly, a Lite Lead sheet made also from rubber and polyvinyl chloride and lead powder was also used and weighted 2.1 kg/m^2. Both samples were obtained from Medical Concepts Australia Pty Ltd.

Fig. 1 shows the plain weave woven fabrics 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, lightweight, durable properties. Kevlar is much stronger than nylon and polyester and it is hoped it will be a long lasting casing material. Fig. 2 shows the weft knitted fabrics used as a comparison in this paper including plated Nylon/Wool (NW), knitted multi-fibre blend (PC) and Kevlar/Wool (KW) fabrics.

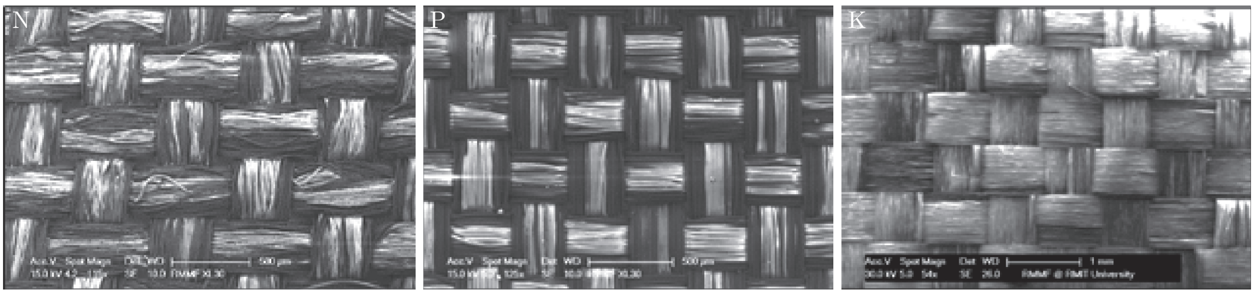


Fig. 1: SEM images for woven fabrics

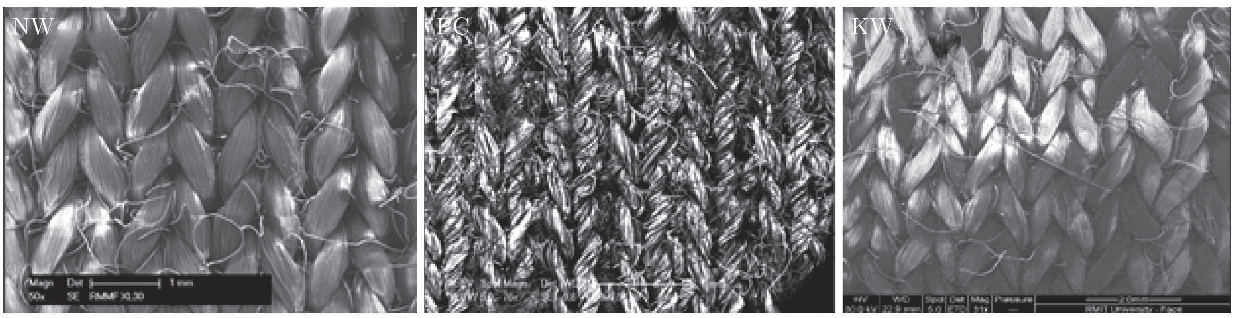


Fig. 2: SEM images for knitted fabrics

Table 1: Material properties

Material code	Material composition	Construction	Density			
			No. of Ends/cm	No. of Wales/cm	No. of Picks/cm	No. of Courses/cm
RL	Regular Lead	Sheet (inner layer)	-	-	-	-
LL	Lite Lead	Sheet (inner layer)	-	-	-	-
N	100% Nylon	Plain woven (outer layer)	14.5	-	12.2	-
NW	Nylon/Wool	Weft knitting single jersey (outer layer)	-	8.6	-	6.2
P	100% Polyester	Plain woven (outer layer)	7.4	-	9.8	-
PC	50% cotton 24% modal 24% bamboo 2% Polyster	Weft knitting double jersey (outer layer)	-	10.6	-	8.2
K	100% Kevlar	Plain woven (outer layer)	8.6	-	9	-
KW	Kevlar/Wool	Weft knitting single jersey (outer layer)	-	7	-	6.2

2.2 Scanning Electron Microscopy (SEM)

A Philips XL30 Field Emission Scanning Electron Microscope was used for the analysis of surface morphology. Samples were prepared by coating them with gold using a sputter coater in an argon-purged chamber for 60 seconds. Then, the specimens were observed in the XL30 SEM chamber at a high voltage of 30.0 kV and 10 mm WD. The magnification was set above 1500×.

2.3 X-ray Measurement

Fabric and lead samples were tested for X-ray attenuation by using a medical X-ray machine (SHIMADZU X-ray system). The distance from the X-ray beam source to the specimen (SID) was 80 cm. Samples were exposed to X-rays at a tube voltage of 80 kVp, and at tube current and time of 12 milliampere-second (mAs). The shielding ability of each sample was evaluated by comparing their transmission doses with the measured transmission doses for reference lead samples. A 'Rad-Check Plus' dosimeter was used to measure the X-ray transmission. The fabric sample size was 15 cm×15 cm. Five different positions, four different corners (or equally spaced points) and the centre of each specimen, were exposed independently and the mean value for each sample was calculated.

2.4 Material Thickness

The material thickness was measured according to the Australian Standard, AS 2001.2.15-1989, determination of the thickness of textile fabrics. The arithmetic mean of five measurements was taken to find the thickness.

2.5 Mass Per Unit Area

The mass per Unit area was measured according to the Australian Standard, AS 1587-1973, determination of mass per unit area and mass per unit length of fabrics. The sample dimensions were 100 mm×100 mm. Fabric weight in g/m^2 was calculated from the weightand area measured according to Eq. (1).

$$g/\mathrm{m}^2 = \frac{W}{A} \tag{1}$$

where, W is the mass of specimen, g. A is the fabric area, m^2.

2.6 Abrasion Resistance

The AS 2001.2.25.2-2006 test method was applied; a Martindale tester performed the experiment. The diameter of the test specimens was cut to $38\pm_{0}^{0.5}$ mm. The dimension of the abradant was 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 was 9 kPa. The weight of each sample was measured before the test was applied and then after the set rubs. The breakdown of the test specimen was observed for each of the established numbers of 5000 rubs and according to the numbers at which specimen breakdown occurs. The determination of breakdown was at 20 000 rubs. All samples were rubbed individually and the arithmetic mean of sample was taken to determine the breakdown and mass before and after rubs. The breakdown point set for test intervals for the abrasion test was from 5000 to 40 000 rubs. The mean of duplicate determinations on four samples was obtained. According to the standard, there are two approaches for assessment of abrasion resistance. Firstly, the sample was abraded until a pre-determined end-point was 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 was to abrade for a set time or number of cycles, and assess the fabric for change in appearance, loss of mass, loss of strength, change in thickness or other relevant property.

2.7 Air Permeability

Air permeability was measured using the Air Permeability tester MO21S by SDL Atlat. The experiment was based on EN ISO 9237.1995, Textiles – determination of permeability of fabrics to air. According to the standard, air permeability is measured as the flow of air per unit area of fabric. The fabric sample size was 80 mm 80 mm, and five measurements were taken. The air permeability (R) is calculated dividing the mean airflow by the test area of the fabric specimen using Eq. (2). It is expressed in millimetres per second.

$$R = \frac{\overline{qv}}{A} \times 167 \tag{2}$$

where, $\overline{qv}$ is the arithmetic mean flow-rate of air. A is the area of fabric under test in square centimetres, A=4.908 cm^2. 167 is the conversion factor from the cubic decimetres.

2.8 Moisture Management

The Moisture Management Tester (MMT) measures the liquid management properties of fabrics according to AATCC TM 195:2009, liquid moisture management properties of textile fabrics. The liquid moisture transport behaviour in different directions of each sample was assessed using five fabric specimens measuring 80 mm×80 mm. The following grading was used for the evaluation:

- Wetting Time (sec) in top and bottom: 1) $\geq$ 120S No wetting; 2) 20-119S Slow; 3) 5-19S Medium; 4) 3-5S Fast; 5) $<$ 3S Very fast.
- Absorption Rate in (%/s) top and bottom: 1) 0-10%/s Very slow; 2) 10-30%/s Slow; 3) 30-50%/s Medium; 4) 50-100%/s Fast; 5) $>$ 100%/s Very fast.
- Max Wetted Radius (mm) in top and bottom: 1) 0-7 mm No wetting; 2) 7-12 mm Small; 3) 12-17 mm Medium; 4) 17-20 mm Fast; 5) $>$ 22 mm Very fast.
- Spreading speed (mm/s) in top and bottom: 1) 0-1 mm/s Very slow; 2) 1-2 mm/s Slow; 3) 2-3 mm/s Medium; 4) 3-4 mm/s Fast; 5) $>$ 4 mm/s Very fast.
- One-way Transport Capacity (OWTC): 1) < -50 Very poor; 2) $-50 - 100$ poor; 3) 100-200 Good; 4) 200-400 Very good; 5) $>$ 400 Excellent.
- Overall Moisture Management Capacity: 1) 0-0.2 Very poor; 2) 0.2-0.4 Poor; 3) 0.4-0.6 Good; 4) 0.6-0.8 Very good; 5) $>$ 0.8 Excellent.

3 Results and Discussion

3.1 X-ray Measurements

Initial X-ray exposure was measured without any fabric and was taken into consideration as a control. Fabrics and lead sheets were measured for X-ray shielding at a medium level of radiation at 80 kVp. The results are shown in Fig. 3 and Fig. 4. The value of the transmittance corresponds with the amount of X-rays that penetrated through the specimen. It indicates the shielding effectiveness of the sample tested. A higher transmittance value corresponds to lower X-ray absorption, meaning that the sample is less effective for radiation protection.

Fig. 3 shows that the transmittance values for RL and LL were 16% and 18%, respectively, indicating that they can absorb most of the X-ray radiation. However, the fabric samples transmitted almost all the X-rays and cannot be considered as having any radiation shielding effect. Since the casing nylon or polyester fabrics have no radiation shielding effects, although their structures are very tight as observed from the SEM images, the primary purpose of using these casing fabrics is to hold X-ray shielding sheets and facilitate cleaning, or facilitate coating as fabric substrate for X-ray protection [14]. Hence, the casing materials should be light for apron weight reduction. Very lightweight fabrics are not considered physically effective radiation shields,

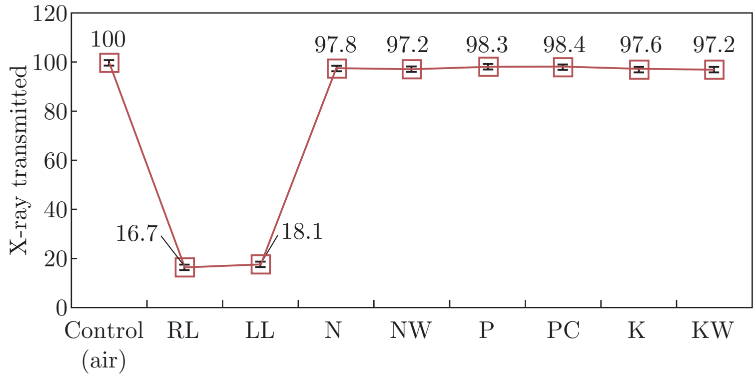


Fig. 3: The amount of X-ray transmitted through different materials (the error bars indicate standard deviation) (%)

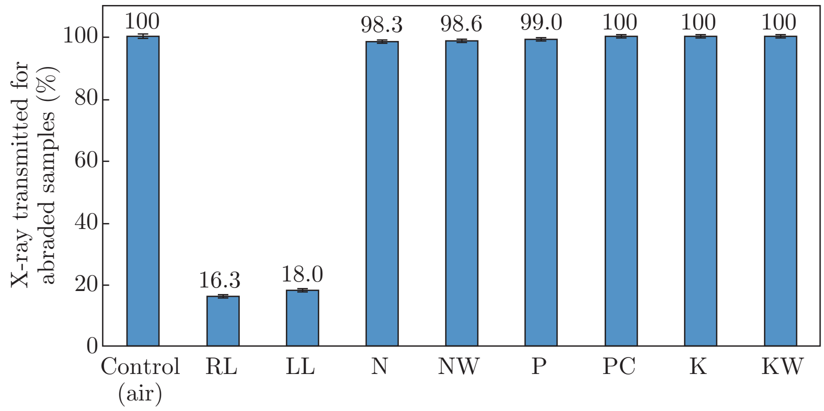


Fig. 4: X-ray transmitted results for samples after abrasion

they would ideally offer the highest possible protection if the fabric was coated with a suitable radiation absorber.

Fig. 4 represented the same sample after 40.000 rubs. It can be seen that there is no change in the shielding efficiency for the lead material. The tiny difference in the shielding efficiency for the lead material was due to the variation of base value of control, air, which could be high if the testing room was exposed to X-ray prior to control measurement. However, the abraded fabric samples have no effect on X-ray protection as indicated by nearly 100% transmitted. Rubbing affected the fabric durability.

3.2 Fabric Physical Properties

Fig. 5 shows the differences of proposed fabrics in thickness and weight. The RL and LL have a heavier weight of 2159 g/m^2 and 2535 g/m^2, respectively, because they were made from lead powder. On the other hand, the KW and NW weigh 520 g/m^2 and 462 g/m^2, respectively, indicating that they are as heavy as the casing material. Samples PC, K, and P are medium to lightweight fabrics. Fabric weight is considered a significant comfort parameter for fabric or industrial garments. Fig. 5 reveals that the heaviest samples are the lead sample (due to the lead particles and PVC sheets). The second heaviest category is the knitted fabrics KW, NW, and PC. The lighter weight is indicated by N 162 g/m^2 and P 154 g/m^2. Thickness typically plays an important role in X-ray transmission, however, the main contribution comes from the high atomic number and the density and atomic cross section of the metal absorbers. The benchmark LL and RL have medium thickness compared to the knitted fabric sample. It is, however, worth noting that the lead samples can be a couple of sheets and must be cased with fabric material. On the opposite side, the knitted plated with wool fabric has the nylon face side, which can be coated with X-ray absorbers, and the next to skin side has the wool to enhanced comfort.

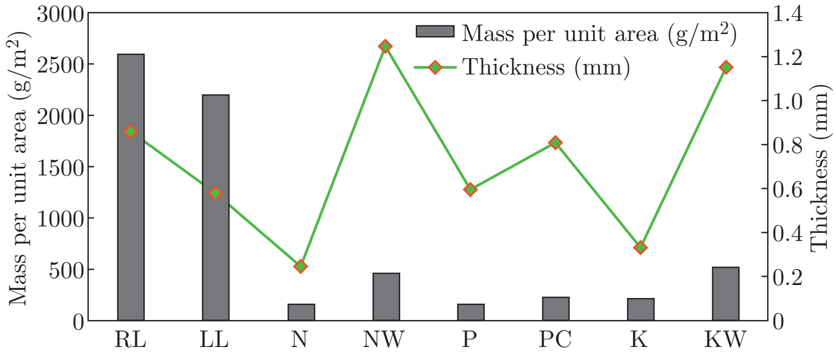


Fig. 5: Mass per unit area and thickness of experiment materials

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. Fig. 5 shows samples N, P, and K are in the medium to low thickness range. They have relatively desirable (medium thickness) comfort characteristics, while all the other samples are in the upper thickness range. In context, the knitting samples NW and KW are the thickest (1.25 mm and 1.15 mm) among the samples, and thicker than the lead sheets. They are likely to have the least desirable comfort characteristics because of their thickness. Hence, these fabrics may not be considered as the casing material.

3.3 Abrasion Resistance

Abrasion is defined as the wearing away of any part of the fabric by 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 [15].

Fig. 6 indicates that the RL and LL samples show less than 1% of mass loss at 40 000 rubs. This could be explained by the material type - polyvinyl lead sheet with a smooth surface. In addition, among all fabrics, the woven samples N and P show the lowest mass loss (3%). Sample P shows a change in colour - a lighter shade than the original fabric colour - at 20 000 rubs. The mass loss at 40,000 rubs is due to the water repellency coating on the commercial lead casing. Surprisingly, the woven sample K displays a higher average mass loss (70%) at almost 25 000 rubs. The colour appearance of K started to fade at 15 000 rubs and indicates that the woven Kevlar fabric is less durable than N and P.

Fig. 6 also shows that the knitted group has fluctuating results in the average of mass loss. For example, PC sample represents the highest mass loss with almost 80% 20 000 rubs. This means that the fabric has less durability to rubbing. KW has a 40% of mass loss at 28 000 rubs and

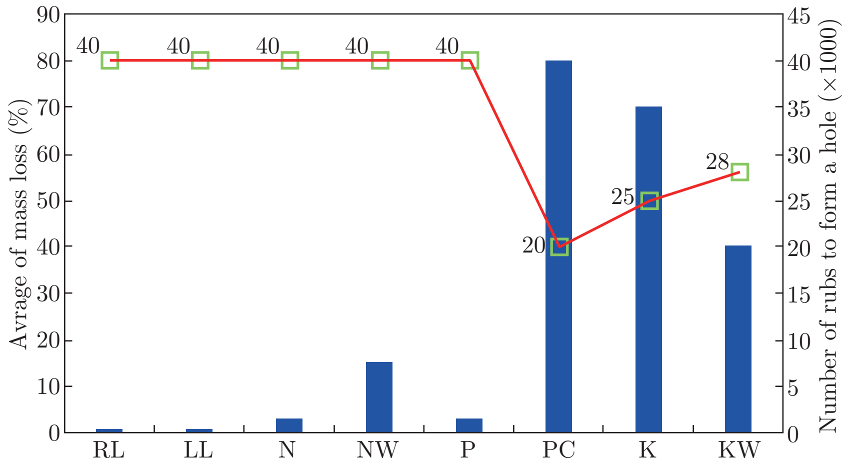


Fig. 6: Abrasion resistance at breakdown

there is a change in colour appearance at 20 000 rubs. The NW sample shows more resistance to rubbing and has a mass loss of 15% only at 40 000 rubs.

In Table 2, images of the samples under magnification show how each sample is affected by the number of rubs shown in Fig. 6. Some represent no change on the surface while others show the breakdown of the knitted thread. Three samples broke completely (PC, K, and KW). The P, N, and NM samples showed more resistance on the surface with only minor colour fading. The lead benchmark revealed a high resistance to abrasion and showed no change to the surface due to the material components - PVC and lead powders.

3.4 Air Permeability

Air permeability, otherwise referred to as breathability, is the ability of a fabric to allow air or moisture vapour moving through it. The air permeability of a fabric can influence a wearer's comfort in several ways. 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, the moisture-vapour permeability and the liquid-moisture transmission are normally closely related to air permeability [13]. Fig. 7 shows the results of the air permeability test. The properties of lead samples LL and RL account for zero air permeability. They cannot leak radiation transmission. Air permeability is not a good feature for protection, but is necessary for comfort. The air permeability results of fabrics

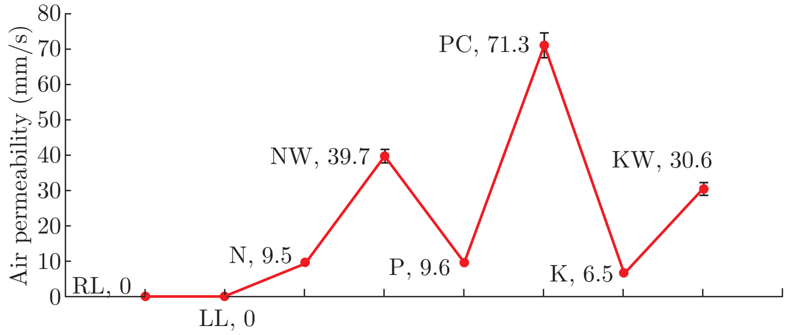
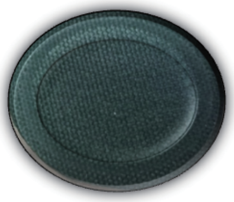
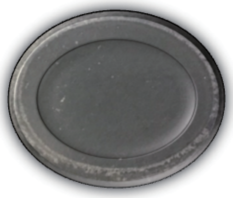
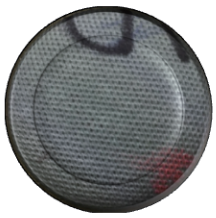
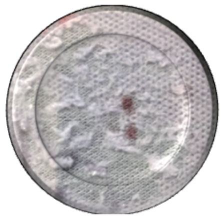
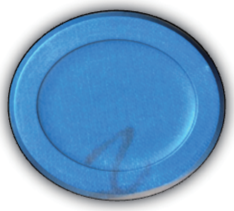
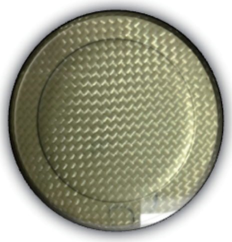
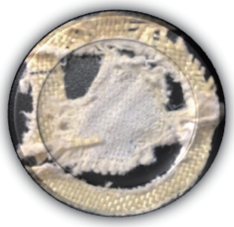
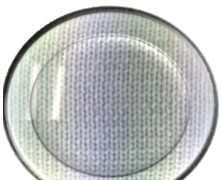
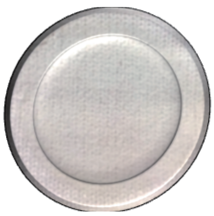
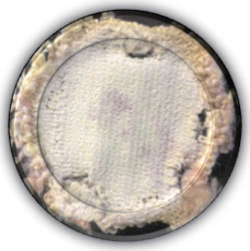


Fig. 7: Air permeability for all samples (the error bars indicate standard deviation)

Table 2: Gallery of samples under magnifying glass before and after apply the abrasion test

Samples before abrasion test apply	Samples after abraded test applied	Samples before abrasion test apply	Samples after abraded test applied
RL		P	
			
LL		PC	
			
N		K	
			
NW		KW	
			

indicate that the PC knitted fabric has the highest breathability attributes among all the samples with 71.3 mm/s. K woven has the lowest air permeability of 6.5 mm/s followed by the N sample with 9.95 mm/s. Finally, KW, NW, and P fabrics have all achieved reasonable permeability. The woven P sample has lower air breathability than knitted samples, KW (30.6 mm/s) and NW (39.7 mm/s). Even though KW contains a similar amount of nylon yarn as NW, the addition of wool yarn made the fabric thicker and created voids between yarns to allow air to easily pass through. This observation supports the report that air permeability depends on the physical properties of fabric such as construction, mass, thickness and yarn count.

The slight permeability to the knitted fabric samples might be due to the open structure of the knit. Fig. 7 shows that the woven sample N, P, and K have lowest permeability compared to the knitted samples. This may be because of the weave structure, plus the water repellency coating on sample P and N for casing the apron.

3.5 Fabric Moisture Management

An individual, for example, wearing RL or LL would experience a clammy or damp sensation because of the non-existent moisture management. Such lead sheets would be uncomfortable to wear for any amount of time, even in a well-ventilated room. Most facilities that utilize radiation tend to prioritize safety over ventilation.

Table 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 the fabric to handle liquid moisture transport. This includes three performance aspects: one-way liquid transportability, moisture drying speed (bottom side maximum spreading speed), and the moisture absorption rate. The larger the OMMC value, the higher the moisture management ability of the sample fabric.

Table 3: Summary of fabric moisture management properties

Sample code	Top surface				Bottom surface				Accumulative one-way transport (%)	OMMC
	Wetting time (s)	Absorption rate (%/s)	Wetted radius (mm)	Spreading speed (mm/s)	Wetting time (s)	Absorption rate (%/s)	Wetted radius (mm)	Spreading speed (mm/s)		
RL	3.95	32.6	5	1.2	120	0	0	0	−588.1	0
LL	9.4	40.6	5	0.5	120	0	0	0	−476.4	0
N	4.8	61.8	5	1	120	0	0	0	−913.5	0
NW	8.7	31.0	14	1.8	4.5	31.0	18	3.1	145.8	0.4
P	5.2	55.2	5	1	120	0	0	1	−850.4	0
PC	4.1	41.0	20	2.6	4.4	43.4	15	2.4	−5.9	0.3
K	4.7	51.7	5	1	120	0	0	0	−902.9	0
KW	6.0	90	10	1.6	7.0	118	21	3.7	548	0.7

The zero OMMC for samples RL, LL, N, P, and K indicates that they have very poor overall moisture management ability. The radiation shielding using naturally dense materials such as pure lead sheets or heavy fabrics compromises thermal comfort. The NW and PC fabrics show poor OMMC, however, the KW fabric has 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 are waterproof due to their very slow water absorption and spreading rate, as well as zero penetration and no liquid moisture transport through thickness.

Fig. 8 shows the fabric max wetted radiuses with moisture absorption and spreading rate. Woven fabric samples N, P and K all have poor liquid moisture management properties with very slow water spreading rates and no wetted areas on the bottom surface. They also have negative or insignificant one-way transport capacities, which indicate that sweat cannot diffuse easily through the fabric. The sweat on the next-to-skin surface on the other side will thus accumulate on top of the surface and result in an uncomfortable wear for the user. On the other hand, the knitted fabric samples NW, PC and KW have medium-to-fast liquid absorption, penetration and spreading rate on the bottom surface of the fabrics. This is due to the blend of the wool/cotton composition (see Table 1). Further research is suggested using knitted plated wool fabric as a base material and coated with X-ray absorber material on the front side [14, 16]. This would save half the weight of casing material for an apron.

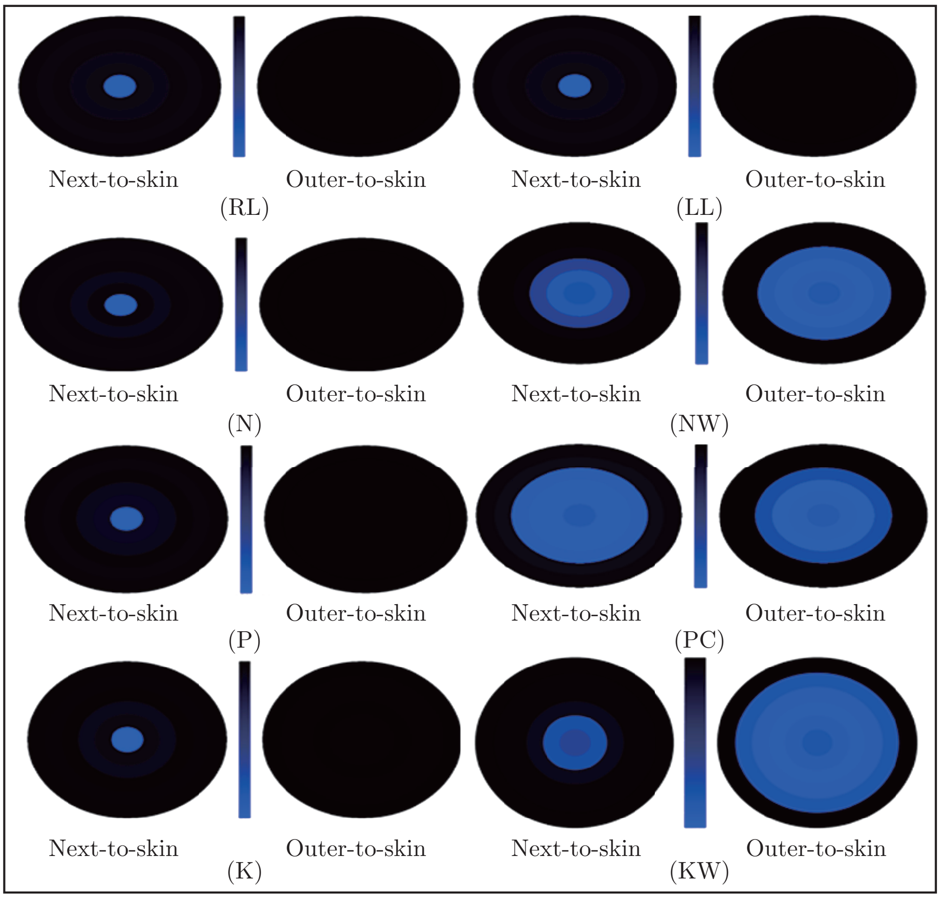


Fig. 8: Max wetted radiuses for all samples

As shown in Table 3 and Fig. 8, the KW sample has the highest absorption rate on the top surface (next-to-skin) with 90% while NW has 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 has zero penetration and thus no one-way transports, slow spreading, and very slow absorption. The characteristic result of most of the samples being slow spreading and 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 [17] about thermal comfort for a similar type of fabric.

Fabric sample N is a very slow absorbing and drying fabric which is characterized as poor one-way transport. It also shows very slow spreading without absorption of moisture, indicating that moisture cannot easily diffuse across the fabric and evaporate into the environment. The NW shows a high absorption rate on the wool surface, suggesting that the wool can absorb water faster than the nylon surface. Hence, the wool face next-to-skin is better for moisture management. Furthermore, the wet-out radius for the top surface is smaller than the bottom surface and the top surface has moderate ability to transfer the absorbed water to the outer surface. Fig. 8

also shows that the wet radius is different between two surfaces for the NW. The NW fabric has a relatively large spreading rate (3.1 mm/s) and large wet-out radius (18 mm) on the bottom, indicating that liquid can spread quickly, transfer easily, and dry quickly on the outer surface of the fabric. The fabric accumulative one-way transport capacity (OWTC) was 145.8%, and the OMMC was 0.4. Therefore, the OMMC and OWTC grade was good, suggesting that the nylon wool-knitted fabric has a moderate water penetration rate between both surfaces. Generally, samples N, P, and K show poor results for moisture management properties.

4 Conclusion

Radiation protection is a critical aspect of the human application of radiation in medical contexts for diagnosis and treatment. This study has evaluated the effectiveness of X-ray aprons to determine their protectiveness and comfort performance. Six fabrics and two commercial lead sheets have been tested and evaluated. The lead sheets have very poor comfort characteristics but excellent radiation shielding ability. On the other hand, the knitted fabric samples like NW, PC and KW show poor absorption of X-ray radiation, and therefore do not have any effective shielding ability. The abrasion resistance of fabric samples used in the study varied. For instance, sample NW has the highest resistance to abrasion, which means it is more durable than KW and PC. Nevertheless, in term of comfort characteristics, the air permeability of all samples varies. LL and RL show an expected zero mm/s liquid moisture spreading rate on the bottom surface due to their zero air permeability. The lead apron material is uncomfortable to wear because of its heavy weight, its non-permeability to air, and inability to absorb and allow for evaporation of liquid moisture. In general, the highest results for air permeability are indicated by samples PC, P, NW and KW. All show good comfort properties, particularly in terms of moisture management. These fabrics could be used for apron casing to replace the woven fabrics which have poor comfort performance. The woven fabrics also show ineffectiveness for radiation shielding. However, all fabrics show enhanced comfort properties compared with lead sheets. The use of knitted fabric plated with wool will improve the comfort performance of the casing material and could be used as a fabric substitute to hold the shielding absorber materials.

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