

REVIEW

Protection Provided by Clothing and Textiles Against Potential Hazards in the Operating Theatre

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The typical hospital and operating theatre present multiple potential hazards to both workers and patients, and protection against some of these is provided through use of various forms of clothing and textiles. While many standards exist for determining the performance of fabrics, most tests are conducted under laboratory conditions and against a single hazard. This paper provides an overview of selected developments in the principal properties of fabrics and garments for use in these workplaces, identifies the key standards, and suggests topics for further investigation.

protective clothing healthcare workers micro-organisms

1. INTRODUCTION

Many situations exist where the permeability of materials and garments to micro-organisms is important, first to wearers in health-related workplaces and, second, in a range of industrial processes (e.g., laundries, filtration plants). The subject is increasingly important as employers and manufacturers grapple with health and safety requirements for protective clothing that really provides protection, and attempts are made to manage diverse features of the environment using various forms of fabrics and garments. The hospital setting presents several potential hazards to workers, the two key ones being control of the thermal environment and control of micro-organisms. Other writers for this issue of the *International Journal of Occupational Safety and Ergonomics (JOSE)* have focussed on thermal properties, so the present paper focusses on control of micro-organisms using apparel and textiles. Nevertheless, providing protection against the transfer of micro-organisms through clothing,

and ensuring that clothing system is thermally acceptable for the wearer, requires both sets of properties to be considered simultaneously. Other performance issues include resistance to cutting and tearing, and cleaning/reuse and/or disposal, but these too are barely addressed in this paper.

The scope of the paper therefore is (a) protection against infectious agents provided by clothing and textiles (material structure and its consistency, material finishing, clothing items and their performance, changes with use), (b) testing and test methods (key variables in testing, standard test methods, and product standards), and (c) unresolved issues. Terms used throughout are defined as

- protective clothing “clothing which covers or replaces personal clothing and which is designed to provide protection against one or more hazards” (p. 62) [1];
- penetration “the process by which a chemical and/or micro-organism moves through porous materials, seams, pinholes, or other

imperfections in a material on a non-molecular level” (p. 58) [1]; and

- protective glove against micro-organisms “at this time it is believed that gloves which resist penetration ... form an effective barrier to bacteria and fungi. This assumption does not apply to protection against viruses” (p. 4) [2].

2. PROTECTION AGAINST INFECTIOUS AGENTS PROVIDED BY CLOTHING AND TEXTILES

The permeability of apparel and apparel fabrics to micro-organisms needs to be considered in relation to the flow of air and liquids (e.g., air, water, blood, serum, urine, other body fluids, varying in viscosity), dimensions of the micro-organism, and where relevant, dimensions also of its carrier such as dust particles and skin debris (e.g., diameter of bacteria 300–10000 nm, virus 30–300 nm, water 0.2 nm [3]; weight), properties of fabrics and fabric layers, and test conditions (differences in temperature, pressure, number of layers).

Several theoretical and empirical approaches to estimating fluid flow through fibrous materials, including apparel fabrics, have been published, some based on the classical structural parameters (fabric sett—warp and weft, fabric mass per unit area, fabric thickness, yarn fineness—warp and weft, fibre and yarn density) (e.g., Militky and Havrdova [4] and Mao and Russell [5]), some based on a capillary-channel theory, and some based on a drag-force theory. Mao and Russell provide examples of published papers related to each theory, and suggest that while most models of permeability for textiles are based on capillary theory, the drag-force theory is relevant to more porous materials such as nonwovens. Nonwovens are widely used in the health sector. While the theories are potentially useful when engineering fabric structures, real improvements in fabrics and garments will be achieved through optimising the two principal competing properties—minimising thermal resistance and maximising transfer of moisture vapour, and preventing the penetration of micro-organisms.

2.1. Material Structure, Performance, and Consistency

The geometric structure of a fabric is known to have a major effect on the permeability of that fabric to air. For tightly woven fabrics, good agreement between air permeability and interfibre pore volume was reported during the mid-20th century (e.g., Robertson [6]), although the relationship between air permeability and construction parameters of more open woven structures has been less clear. During the past 50 years, many developments in fabric constructions and finishing have occurred, including structures developed or modified for use by healthcare workers. For example, the performance of woven and nonwoven fabrics has been compared. The barrier effectiveness against *E. coli* and *S. aureus* of woven (plain weaves, cotton, cotton/polyester blends, 100% polyester) and nonwoven (three-layer sandwich, randomly laid spun-bond web upper and lower with a melt-blown layer between, wood pulp, and polyester) fabrics from surgical gowns was shown to relate to the size of interstitial spaces (pore size), smaller spaces generally corresponding to higher barrier properties [7]. Interestingly, high ratings of fabric repellency for water and oil were not consistently linked to superior barrier effectiveness, and although a fabric may have wetted easily, bacterial transmission tended not to occur if the fabric cover was high (i.e., yarns were packed tightly). Visible liquid breakthrough thus does not necessarily indicate transmission of the organisms. The barrier effectiveness of the nonwoven fabrics was generally superior to that of the wovens, and while one might have expected superior performance from reinforced fabrics included in the study, this was not evident [7].

Improving barrier effectiveness has been sought through laminating a film (typically monolithic) to a fabric substrate, but while normally improving resistance to penetration by micro-organisms, resistance to permeation of water vapour tends also to be increased (an undesirable effect for wearers of garments made in the fabrics). Thus, from the mid-1990s, various forms of permeable film have been used, and the

performance of these determined. For example, microporous and monolithic films have been compared (e.g., Barnes, McCord, Tucker, et al. [8]). Viral penetration and transfer of heat and moisture were examined. The microporous films failed to prevent the virus passing through them, whereas the monolithic ones were effective; the microporous films were only slightly superior in the other two properties. A minimum pore size for resistance to viral penetration of $\sim 0.05 \mu\text{m}$ has been defined (polycarbonate membrane), the authors also noting that viral penetration through a fabric may occur in the absence of visible fluid strike-through [8]. In a study on surgical masks and dust/mist respirators, airborne micro-organisms in the 1–5 μm range were considered the lower limit for mask resistance [9]. Directional differences in dimensions of micro-organisms were noted (i.e., spherical compared with rod-shaped) [9]. A comprehensive review of literature on rubber, latex, and vinyls as used in the manufacture, finishing, and performance of protective gloves was published in 1999 and focussed on problems which surgical gloves present in surgical practice [10]. Issues of powder-induced peritonitis and adhesions, hypersensitivity to latex rubber, and glove perforations were addressed.

Properties across a fabric/product are known to be variable and under some circumstances, this variability could lead to compromised protection during use. The porosity (permeability) of a woven fabric has been shown as variable within that fabric (e.g., Militky and Havrdova [4]). Several studies on variability among batches of gloves have been undertaken, some related to protection against chemical hazards rather than micro-organisms (e.g., Perkins and Pool [11]). Testing for defects in new gloves (e.g., Kotilainen, Avato, and Gantz [12]), and evaluating the desirability of surgical gloves being individually- or batch-tested for leaks prior to sale as a check on variability/faults, have also been undertaken (e.g., Jamal and Wilkinson [13]) with no evidence of significant differences in leakage between 100% testing and batch testing. However, the microporosity of the gloves increased during use (i.e., became less resistant to

penetration by micro-organisms) [13]. (See also section 2.4.1.)

2.2. Material Finishing

A variety of finishing treatments has been applied to textiles in order to inhibit growth of micro-organisms, perhaps influencing the consequential transmission through fabrics (although no evidence to this effect has been identified). These treatments include addition of metals or organic compounds at the fibre, yarn, or fabric stage. Silver, e.g., is currently in use and has been shown to be effective in inhibiting bacterial growth (*S. aureus*, *E. coli*) (and importantly is not noxious to the skin) [14]. This work of Lee and Jeong [14] indicated smaller-sized silver particles in colloidal solution had superior antibacterial effect than those of a larger size (diameter 2–3 μm , $\sim 30 \mu\text{m}$). Copper after-treatments are also used to improve antibacterial properties of cotton fabrics [15] (with changes in interstitial space dimensions observed), but no application to use of these fabrics by healthcare workers has been identified. Antibacterial treatments would seem most relevant for nondisposable products. Other fabric treatments are comparable to those for waterproofing and sometimes their use and performance have been extrapolated to liquids such as those containing micro-organisms, without necessarily providing supporting evidence.

2.3. Clothing Items and Their Performance

During the 1960s and 1970s, several studies on clothing assemblies for operating rooms were conducted (e.g., Blowers and McCluskey [16] and Clark and Mullan [17]), with comparisons made between products manufactured from different materials (e.g., woven cotton, film), different designs (e.g., two-piece garment systems, aprons), and different wearers. More recent studies on the performance of garments in woven fabrics (barrier, re-usable) and a range of nonwoven materials (primarily limited use or disposable) have been reported (e.g., Hao et al. [3], Ukpabi and Obendorf [18], and Mitchell, Evans, and Kerr [19]). A consistent finding is

that while impermeable materials are effective in reducing transfer of micro-organisms, because they also have limited permeability to moisture vapour, the thermoneutrality of the wearer is compromised.

Surgical and examination gloves have been used for over 100 years, providing a barrier between the surgeon and the patient. However, their use is not problem-free, and glove-related problems were reviewed during the late 1990s [10]. A number of papers published during the last 15–20 years addressed the performance of surgical gloves: the incidence of glove perforation and bacterial contamination (e.g., Dodds, Guy, Peacock, et al. [20]), surgical gloves as a barrier against human immunodeficiency viruses (e.g., Dalgleish and Malkovsky [21]), failure of nonlatex surgical gloves [22], and leakage (viral) after simulated use of vinyl and latex examination gloves (e.g., Korniewicz, Laughon, Cyr, et al. [23]).

Footwear is a potentially significant clothing item in the spread of disease (recall agricultural controls in the UK in 2001). Footwear decontamination and the use of disposable footwear covers are two means of minimising transfer. However, effectiveness of footwear decontamination units was investigated during the 1970s (e.g., Braymen, Songer, and Sullivan [24]) and as reliance on such units was found to be unwarranted, use of disposable products continues to be recommended.

2.4. Changes With Use

2.4.1. Conditions of use

Conditions under which a material is used (and tested) can affect the reported and observed permeability to micro-organisms. For example, air permeability of some textiles has been shown to depend on humidity. Gibson, Rivin, Kendrick, et al. [25] demonstrated the effects which differences in humidity have on measured permeability to air for various types of materials, tightly-woven fabrics showing higher humidity dependence because of smaller initial interstitial spaces. These findings are likely to be relevant to the permeability of materials to micro-organisms

in that they affect fluid flow. And because wetting a material affects the flow of air through many materials (e.g., Belkacemi and Broadbent [26]), such a change also has the potential to change the passage of micro-organisms. Whether the change is an increase or a decrease remains fabric-dependent. One might consider that because the fabric has absorbed liquid, the yarns and/or fibres in the fabric have expanded with a consequential reduction in dimensions of the interstitial spaces and reduced penetration. Conversely, one might consider that because the fabric is wetted, the liquid (carrying micro-organisms) contributes to increased penetration. Practical implications of the findings on humidity-dependence and wetting are not clear, and warrant further study.

Permeability to micro-organisms may change during a single period of use (e.g., changes in humidity and temperature of a garment microclimate) or, worse, prior to use. The paper packaging used for a range of sterile surgical gloves was identified as being permeable to gram-positive bacteria, thus a potential contaminant prior to use [27], and the microporosity of glove materials can change during use [13]. Further evidence of changes in use relates to tensile strength and general barrier integrity of various forms of medical gloves (nonsterile vinyl, sterile vinyl, nonsterile natural rubber latex) (e.g., Douglas, Simon, and Goddard [28]). Leakage rates of $\leq 2\%$ in new gloves, irrespective of type, and of 3–28% after use (sterile vinyl gloves at the low end, nonsterile vinyl gloves at the high end) have been reported [28], although the decrement in performance was not related specifically to observed changes in tensile strength.

2.4.2. Multiple layers

In use, a product may comprise several layers, either as part of one product, or as several products worn simultaneously as an assembly. Several papers on masks typically constructed from two or more layers of material have been published. Double- and/or triple-gloving is also practised by some to compensate for adverse effects of physical glove perforations which occur as a result of needle-stick or for other reasons (e.g., Lars, Naver, and Goltrup [29] and

Laine and Aarnio [30]). While fewer micro-organisms are likely to penetrate multiple layers compared with a single layer of the same fabric under identical conditions, the air permeability will be reduced with fabric layering, in one study reportedly by ~50% from one to two layers, a further ~25–30% from two to three layers, and further smaller reductions with additional layers (using two woven fabrics typical of those used in clean rooms) [4].

2.4.3. Soiling and cleaning

Many products used in the healthcare sector are disposable, so the effects of use and cleaning on permeability to micro-organisms are not relevant. Nevertheless, availability of limited- and multiple-use products implies successful cleaning can be carried out. The questions then are, can this be satisfactorily achieved, and can it be achieved for all product types? A theoretical rationale is considered by some to be insufficient defence for a practice such as laundering of scrub clothing (e.g., Belkin [31]). Much of scrub clothing is made from polyester/cotton blends or 100% polyester fabrics, so use of high water temperatures and chlorine bleaches, generally effective in disinfection, are not possible. However, few studies on cleaning have been identified and whether this topic warrants further investigation is unclear.

3. TESTING AND TEST METHODS

3.1. Key Variables in Testing

Concern with the transmission of infectious agents, viruses in particular, prompted scrutiny of methods of testing barrier materials from the 1980s through to the present (e.g., Kotilainen et al. [12] and McCullough and Schoenberger [32]). Test methods used normally are described in published research papers on fabrics and garments, and readers are alerted to variables which may affect results reported:

- ambient humidity and ambient temperature;
- regain of fabric and conditioning prior to testing;

- pressure and temperature gradients between each surface of fabric, if present;
- fabric compression as a test variable;
- precision of instruments for detecting pass/fail (visual assessment of breakthrough or instrumental detection); and
- properties of the challenge agent (e.g., viscosity of carrier fluid, type of organism).

Failure of a fabric is typically identified by visible liquid breakthrough. However, liquid breakthrough does not always result in the penetration of bacteria, and further, viral penetration can occur without evidence of liquid breakthrough. The definition of the European Committee for Standardization (CEN) of protective clothing against micro-organisms confirms the need for caution in this regard [3].

3.2. Standard Test Methods and Product Standards

The following test methods were current at the time the article went to press, but the list does not include, as separate entries, those International Organization for Standardization (ISO) standards which have been endorsed for use in a country or group of countries (e.g., each member of the European Union). Such endorsements imply the standard is identical (other than the prefix), but readers need to be aware of possible variations from the ISO, normally included as an appendix to the standard. The list also does not include a draft standard at the discussion or final discussion stage (i.e., DIS, FDIS), nor does it include standards on more general performance properties of materials for hospital use (e.g., resistance to abrasion, resistance to puncture).

The existence of several standards purportedly determining the same or similar properties of protective clothing or clothing materials requires the reader/user to be alert to differences, often subtle, in the methods and conditions required in a test. Such differences can lead to differences in results and thus inappropriate comparisons. Many published tests note test limitations and provide cautionary comments for interpretation of results.

- General: (a) international standards: ISO 16604:2004 [33], ISO 16603:2004 [34], ISO 13688:1998 [35], (b) regional/national standards: ASTM F1819-07 [36], ASTM F1671-07 [37], ASTM F1670-07 [38], ASTM F903-03:2004 [39], ASTM F51-00:2002 [40], CEN TR 15321:2006 [41], EN 340:2004 [42], EN 14126:2003 [43];
- surgical masks: (a) international standard: ISO 22609:2004 [44], (b) regional/national standards: ASTM F2100-07 [45], ASTM F2101-07 [46], ASTM F1862-07 [47], ASTM F2299-03 [48], EN 14683:2005 [49];
- drapes, gowns, clean air suits: (a) international standards: ISO 22610:2006 [50], ISO 11810-1:2005 [51], (b) regional/national standards: ASTM F2407-06 [52], EN 13795-1:2002 [53], EN 13795-2:2005 [54], EN 13795-3:2006 [55]; and
- gloves: (a) international standards: ISO 10282:2002 [56], ISO 10282:2002/Cor1:2005 [57], ISO 11193-1:2002 [58], ISO 11193-1:2002/Cor1:2005 [59], (b) regional/national standards: ASTM D3577-06 [60], ASTM D3578-05 [61], EN 374-1:2003 [2], EN 374-2:2003 [62], EN 420:2003 [63].

4. UNRESOLVED ISSUES

This review does not purport to be comprehensive, but was written to raise awareness of issues on protection against micro-organisms which clothing and textiles can provide. Many questions have yet to be answered. For example, is there an optimum interstitial dimension which prevents the passage of micro-organisms yet allows the passage of moisture vapour, or do fabric surface treatments have a more important effect? Do we really understand the humidity-dependent transmission? Are more-recently developed semipermeable fabrics sufficiently resistant to the passage of micro-organisms? Should antimicrobial treatments of fabrics for use in the healthcare sector be increased, or does the comparatively short product life render this inappropriate? To what extent are international and/or de facto international standards (i.e., ISO, EN) for test methods and product performance

criteria used in later developing countries (e.g., China, Vietnam), and to what extent are protective products sourced from these countries? Given a world need to reduce solid waste and/or use compostible materials, ought manufacturers servicing the healthcare sector to continue to focus on disposables?

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