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Major Article

Impact of surface tension on the barrier performance of gowns and coveralls

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Background: Health care workers and laboratory workers who are routinely exposed to potentially life-threatening infectious diseases should wear protective clothing when anticipating contact with infectious materials. The most critical property of protective clothing is its ability to prevent liquids and viruses from passing through the garment. There are a number of potentially infectious liquids that workers may be exposed to during routine tasks. Each liquid has different physical and chemical properties that affect penetration. However, the current test methods use a limited number of liquids for classifying the barrier performance. The impact of the surface tension of the challenge liquid on the penetration resistance of gowns and coveralls was investigated in this study.

Methods: Eight isolation gowns and 2 coveralls were tested in accordance with American Association of Textile Chemists and Colorists 42 and American Association of Textile Chemists and Colorists 127 test methods, which were modified to incorporate the substitute challenge liquids.

Results: Although current standard test methods only use water to categorize the liquid penetration resistance of minimal to moderate barrier performance gowns, a significant difference in the penetration was found when simulated body fluids were used.

Conclusions: The results suggest that safety professionals and wearers should consider the varying barrier performance of personal protective equipment with different liquids and the use limitations when selecting them for the required tasks. Furthermore, standard development organizations should consider multiple challenge liquids when classifying protective clothing for health care settings.

BACKGROUND

The liquid penetration resistance of materials used in the construction of gowns has become increasingly important to health care workers (HCWs) due to the risk of infections caused by bloodborne pathogens. It is well known that blood can carry viruses and bacteria with it wherever it penetrates. Previous studies reported that if the liquid penetrates 1 layer, it will eventually go through additional layers of the same fabric.[1] Thus, it is vital that liquid barrier properties of the fabrics used in the construction of HCW protective clothing be evaluated by means of standardized test methods that simulate occupational exposures. Additionally, according to the Occupational Safety and Health Administration's Bloodborne Pathogens Standard, PPE is considered "appropriate" only if it does not permit blood or other potentially infectious materials to pass through to or reach the employee's work clothes, street clothes, undergarments, skin, eyes, mouth, or other mucous membranes under normal conditions of use and for the duration of time for which the protective equipment will be used (1910.1030(d)(3)(i)).

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Table 1
ANSI/AAMI PB 70:12 classification of the barrier performance of surgical gowns, other protective apparel, surgical drapes, and drape accessories

Level*	Test	Liquid challenge	Result	Expected barrier effectiveness†
1	AATCC 42 Impact Penetration‡	Water	≤4.5 g	Minimal water resistance (some resistance to water spray)
2	AATCC 42 Impact Penetration	Water	≤1.0 g	Low water resistance (resistant to water spray and some resistance to water penetration under constant contact with increasing pressure)
	AATCC 127 Hydrostatic Pressur§	Water	≥20 cm	
3	AATCC 42 Impact Penetration	Water	≤1.0 g	Moderate water resistance (resistant to water spray and some resistance to water penetration under constant contact with increasing pressure)
	AATCC 127 Hydrostatic Pressure	Water	≥50 cm	
4	ASTM F1670 Synthetic Blood Penetration Test (for surgical drapes)	Synthetic blood	no penetration at 2 psi (13.8 kPa)	Blood and viral penetration resistance (2 psi)
	ASTM F1671 Viral Penetration Test (for surgical and isolation gowns)	Nutrient broth with Bacteriophage Phi-X174	No penetration at 2 psi (13.8 kPa)	

ANSI/AAMI, American National Standards Institute/Association for the Advancement of Medical Instrumentation; *ASTM*, ASTM International.
*In order of increasing protection.
†Wearers would expect this level of barrier effectiveness based on the performance standards.
‡American Association of Textile Chemists and Colorists (AATCC) 42 Water resistance: impact penetration test determines the ability of a material to resist water penetration under spray impact.
§AATCC 127 Water resistance: hydrostatic pressure test determines the ability of a material to resist water penetration under constant contact with increasing pressure.

HCWs are routinely exposed to splashes and sprays of blood or other potentially infectious body fluids when performing health care tasks. They may also immerse their hands in basins or body cavities containing body fluids such as blood, urine, amniotic fluid, saliva, sweat, feces, and vomit. Blood, perspiration, iodine, and alcohol may act as carriers transporting bacteria and viruses through fabrics in the operating theater.[2]

Performance standards are available to define the requirements for clothing or clothing materials used to protect against infectious agents. In the United States, the American National Standards Institute/Association for the Advancement of Medical Instrumentation (AAMI) PB70[3] has established a classification system for protective apparel used in health care facilities, based on their liquid barrier performance. The American National Standards Institute/AAMI PB70 (AAMI PB70 hereafter) standard includes 4 test methods to evaluate the barrier effectiveness of surgical gowns, isolation gowns, and surgical drapes. Based on the results of these standardized tests, 4 levels of barrier performance are defined, ranging from Level 1, the lowest level of protection, to Level 4, the highest level of protection (Table 1). According to AAMI PB70, Level 4 gowns are the only category of gowns that need to be tested for viral penetration resistance using a challenge liquid with a surface tension simulative of body fluids. However, the majority of gowns on the US market that most likely fail to achieve Level 4 requirements are categorized as Levels 1-3, depending on how well they resist water. These gowns are typically used during isolation or surgical procedures that may involve a minimal to moderate degree of exposure to fluids.

A companion technical information report, AAMI Technical Information Report (TIR) 11,[4] recommends that the risk of anticipated exposure to blood or body fluids should be assessed before a decision is made on the level of protection needed. According to this guidance document, Level 1-3 gowns could be worn during procedures posing a lower risk of fluid exposure, such as minor ear, nose, and throat procedures and arthroscopic orthopedic procedures that typically involve minimal to moderate body fluid exposures. Importantly, gowns in Levels 1-3 are tested only for water resistance. Therefore, such classification standards may not provide an accurate representation of the protection provided when worn for patient care, although they do provide information regarding the *relative* protection levels provided by fabrics. The liquid penetration resistance of fabrics depends on several parameters, including the fabric's physicochemical properties (eg, material thickness, pore size), characteristics of microbial carriers (eg, surface tension, viscosity, contact angle), and external factors such as physical, chemical, and thermal stresses that are applied to the fabric (eg, pressure, time).[5-7] Hypothetically, fabric resistance to liquid penetration should increase with increasing liquid surface tension, viscosity, the contact angle formed with the fabric material, and fabric thickness, and should decrease with an increase in time, liquid pressure, and pore radius.[8]

Although the water resistance properties of gowns may be utilized to conceptualize their protective properties, water resistance may not be representative of resistance properties for other liquids. Relying on water as a surrogate may mislead the wearers to falsely believe that an equal degree of protection is provided when exposed to blood or body fluids.[7] A number of studies[9-13] have been conducted to compare the penetration between liquids. However, additional research is needed to account for the changes in the materials used in protective clothing construction and the properties of the challenge liquids available today. In addition, there is an absence of studies conducted after the publication of AAMI PB70 (a standard that specifies test methods for protective gowns currently available), further complicating the interpretation of previous studies. Therefore, in this study, we investigated the effect of the challenge liquid's surface tension on the penetration properties of protective clothing that are currently available on the market, using the test methods specified in AAMI PB70. To understand the effect of surface tension of the challenge liquids, fabric samples taken from continuous and discontinuous regions (seamed areas) of gowns and coveralls were tested using 3 liquids: water, a simulated body fluid with reduced surface tension (SBF), and synthetic blood.

METHODS

An experimental laboratory study was designed to investigate the impact of surface tension of the challenge liquid on the liquid penetration resistance of selected protective clothing, including isolation gowns and coveralls. Eight isolation gowns and 2 coveralls were tested in accordance with American Association of Textile Chemists and Colorists (AATCC) 42[14] and AATCC 127[15] test methods, which were modified to incorporate the substitute challenge liquids.

Protective clothing fabrics

The test materials selected for this study were chosen to represent a wide range of protective clothing used in health care settings. They were selected based on the market review (before the COVID-19 pandemic) as well as communications with organizations that use large amounts of protective clothing: the Assistant Secretary for Preparedness and Response's Strategic National Stockpile, U.S. Ebola Treatment Centers, Veterans Affairs Hospitals,

Table 2
Characteristics of the tested protective clothing

Sample ID	AAMI level	Description	Fabric type	Seam type	Thickness (mm)	Weight (g/m^2)	Air permeability (cfm/sf)
3G	No claim	Impervious plastic film isolation gown	A single layer of polyethylene (plastic) film	Heat sealed	0.08	23.4	0.435
13G	No claim	Spunbond polypropylene isolation gown	Spunbond polypropylene/light nonwoven	Stitched	0.132	20.3	747
2G	No claim	Poly-coated isolation gown	Polyethylene-coated spunbond polypropylene/nonwoven	Stitched	0.252	42.6	0.44
10G	Level 2	Multilayer isolation gowns for light to moderate fluid pressure conditions	Polypropylene SMS/medium-weight multiply nonwoven	Heat sealed	0.18	25.9	89.97
12G	Level 2	Medium-weight, multiply gown for light to moderate pressure conditions	Polypropylene SMS/medium weight-multiply nonwoven	Heat sealed	0.172	20.8	107.5
14G	Level 2	Medium-weight, multiply, isolation gown	Polypropylene SMS/medium-weight multiply nonwoven	Heat sealed	0.18	22.4	102.57
11G	Level 3	Comfortable and breathable premium isolation gown	Polypropylene SMS/medium-weight multiply nonwoven	Heat sealed	0.332	44. 7	50.86
6G	Level 3	Trilayer isolation gown	Heavy-weight polypropylene SMS nonwoven	Heat sealed	0.24	38.5	48.14
2C	(ISO 16603 Class 3/6)	Coverall	Flash-spun polyethylene fabric	Serged and overtaped	0.18	47.3	0.51
1C	(ISO 16603 Class 6/6 and ISO 16604 Class 4/6)	Coverall	Laminated flash-spun polyethylene fabric	Serged and overtaped	0.2	62.4	0.44

AAMI, Association for the Advancement of Medical Instrumentation; *SMS*, spunbond-meltblown-spunbond.

and The National Ebola Training and Education Center. The samples used in this study were purchased from the open market and were identified as widely used isolation gowns and coveralls in the US market. Protective clothing made from single-layer nonwoven fabrics, films, multiple-layer nonwoven fabrics, and fabrics reinforced with film or coating were included in the test samples. The barrier performance of the samples included gowns without AAMI PB70 claims as well as AAMI PB70 Level 2 through Level 3 gowns. Also, 2 coverall models with high water and synthetic blood resistance claims were included in the set.

Ten different protective clothing models used in the study were categorized by their fabric types and seam types in addition to their AAMI PB70 levels. There were 3 isolation gown models in the sample set without any AAMI PB70 claims and 2 coveralls for which AAMI PB70 does not apply (coded as Not Applicable—NA). Only AAMI PB70 Level 2 and 3 gowns were included in the main analysis since the uncontrolled fabric properties are expected to skew the results of the analysis. For example, although 2G, 3G, and 13G gown models do not have any AAMI PB70 claims; their barrier resistance differs widely within the group. This is due to the distinct differences in their fabric types (laminated nonwoven, film, and light nonwoven) and seam types (stitched and heat sealed) in terms of barrier resistance. Both 2G and 3G models have excellent barrier properties compared to all the other isolation gown models; however, the discontinuous regions of 2G do not provide much barrier due to the stitched seams. All AAMI PB70 Level 2 and 3 gowns could be compared to each other since all of them were constructed with nonwoven fabrics and sealed with the same type of seams (heat sealed). Although 13G was not included in the analysis, mean AATCC 127 and 42 values were reported in this paper for comparison.

The 2 coveralls included in the study did not have any AAMI PB70 claims, as coveralls are out of the scope of the standard; however, the manufacturer's technical data for both coverall models report AATCC 42 and AATCC 127 water resistance values above the minimum criteria listed for AAMI PB70 Level 3 gowns. The manufacturer of one of the coveralls reported that the coverall is classified as Class 6/6 when tested according to the International Organization for Standardization (ISO) 16603 blood penetration test[16] and as Class 4/6 when tested according to the ISO 16604[17] viral penetration test. When the pressure levels are compared, Class 4 pressure level is equivalent to almost half of the pressure (7 kPa vs 13.78 kPa) level that **American Society for Testing and Materials International** (ASTM) F1671[18] uses. Also, Class 6 testing requires exposure of the fabrics to much higher pressures compared to the ASTM F1670 blood penetration test[19] (20 kPa vs 13.78 kPa). The other coverall model only passes ISO 16603 at the 3.5 kPa pressure level and therefore is classified as Class 3/6. Thus, these 2 coverall models could be evaluated as[16] borderline between AAMI PB70 Levels 3 and 4.

Fabrics cut from protective clothing were characterized for weight and thickness (see Table 2) following the ASTM D1777 Standard Method for Measuring Thickness of Textile Materials[20] and the ASTM D3776 Standard Method for Mass per Unit Area of a Woven Fabric.[21] In addition to barrier performance, the air permeability of the samples was also assessed using the ASTM D737 method,[22] and 10 replicates per protective clothing model were used. Table 2 also provides general information for the tested protective clothing. Additionally, it includes the descriptions from the manufacturers of the protective clothing.

Test liquids and characterization

Previous studies have reported that liquid type has a significant effect on liquid barrier testing.[9,12] In our study, the effect of surface tension of the challenge liquid on the liquid penetration of protective clothing fabrics was compared using 2 different barrier resistance testing methods (AATCC 42 Impact Penetration test and AATCC 127

Hydrostatic Pressure test) and 3 different challenge liquids (distilled water, SBF, and synthetic blood). Liquids were characterized by measuring the surface tension, relative viscosity, density, and contact angle between the fabrics and liquids.

The surface tension for a number of human body fluids varies between 0.027 and 0.075 N/m, with an average of 0.040 N/m at 20-25 °C, while the surface tension of water is 0.072 N/m.[7,19] ASTM F1670[19] and ISO 16603[16] specify the use of synthetic blood with a surface tension of 0.042 ± 0.02 N/m to simulate most body fluids; therefore, in this study, a challenge liquid was prepared using deionized water and a surfactant (0.03% w/w solution of Surfynol 104H, Air Products, Vandalia, IL), which was suggested in ASTM F1359[23] to have a surface tension of approximately 0.042 ± 0.02 N/m. The surface tension of distilled water was measured as 0.070 ± 0.02 N/m. The surface tension of all the liquids used in this study was measured using a du Noüy precision tensiometer (CSC Scientific Co Inc.), as per the manufacturer's instructions.

Previous research has shown that synthetic blood is a suitable substitute for real blood[24] and many test methods including ASTM F1670[19] specify the use of synthetic blood; therefore, synthetic blood was included in the challenge liquids of this study. Synthetic blood, which was delivered in plastic containers (Johnson Moen & Co), was made from distilled water, a thickening agent (Acrysol G111, Rohm & Hass Co), and a red dye containing a colorant and a surfactant (Direct Red 081), with 0.042 ± 0.02 N/m reported surface tension value. The surface tension of the synthetic blood was measured to be between 0.053 and 0.056 N/m during the testing using the du Noüy ring method. The surface tension results aligned with the recent study where values of 0.052-0.061 N/m were reported, as open atmosphere, temperature, liquid disturbance, and humidity play an important role in the surface tension of synthetic blood.[25] Thus, synthetic blood was replenished in the test cell after every measurement during the AATCC 127 testing.[15] The contact angle between these liquids and each of the protective clothing fabric was also measured by a Theta Lite optical tensiometer (Biolin Scientific) (see Table 3). The mean density of distilled water, SBF, and synthetic blood was measured as 0.98, 0.99, and 0.98 g/cm^3, respectively. The mean viscosity of distilled water, SBF, and synthetic blood was measured as 1.06, 1.06, and 7.71 cP, respectively.

Test methods

AAMI PB70 lists 2 standardized testing procedures for liquid penetration to set the criteria for Levels 1, 2, and 3 surgical and isolation gown fabrics (Table 1). To measure the effect of surface tension of the fluid on the barrier performance of the protective clothing, liquid penetration was measured following AATCC 42 Water Resistance: Impact Penetration test[14] and AATCC 127 Water Resistance: Hydrostatic Pressure test[15] methods as described in AAMI PB70.[3] AAMI PB70 requires testing to be conducted using distilled water. Consistent with the standard, distilled water was used in the current study. The barrier performance of the samples was also assessed using 2 additional liquids: SBF and synthetic blood. The same procedure was used for all the 3 liquids.

AATCC 42 Water Resistance: Impact Penetration test determines the ability of a material to resist water penetration under spray impact. In this test procedure, 500 ml of liquid was poured into the funnel of the tester and allowed to spray from a height of approximately 50 cm onto the surface of a sample supported by a weighed blotter (Ahlstrom Grade 989). The increase in weight of the blotter was assessed in grams using a scale (Ohaus Pioneer Model #PA512 accurate to 0.01 g) and then calculated to determine the liquid penetration. The nozzles used in the water impact penetration test were rinsed thoroughly and dried between uses of different types of liquids. The clamping surface was dried prior to each specimen being clamped. Thirteen specimens taken from each critical zone (chest and sleeve seams) were tested using 2

Table 3
Contact angle results (min, max, and mean) with 3 challenge liquids

Sample ID	Contact angle (°)								
	SBF			Synthetic blood			Distilled water		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
3G	68	86	79	89	106	98	108	120	114
13G	97	151	130	119	144	130	130	152	139
2G	68	79	74	94	108	101	103	115	106
10G	108	139	123	125	143	134	106	153	136
12G	103	163	131	119	150	134	118	158	143
14G	113	153	129	123	142	132	129	141	135
11G	113	147	127	121	148	136	131	150	139
6G	97	160	129	128	143	135	111	165	146
2C	54	91	67	86	105	95	89	123	105
1C	70	83	77	87	105	97	92	111	102

SBF, simulated body fluid.

different challenge liquids (water and SBF) using the AATCC 42 method. Given the amount of liquid required in the AATCC 42 test, 3 specimens (the minimum required number of samples per AATCC 42 standard) were tested using synthetic blood. In sum, 290 AATCC 42 experiments ((26 replicates × 5 Level 2 and Level 3 fabrics × 2 regions × 2 challenge liquids) + (3 replicates × 5 Level 2 and Level 3 fabrics × 2 regions × 1 challenge liquid)) were conducted across the conditions of the study for AAMI PB70 Level 2 and Level 3 gowns (Table 4). Also, 290 AATCC 42 experiments were conducted for 3 gowns without AAMI PB70 claims and 2 coveralls. Images of the front surfaces of the fabrics on which synthetic blood was poured were also developed.

The hydrostatic pressure test was performed according to AATCC 127. A test specimen mounted under the orifice of a conical well was subjected to water pressure constantly increasing at 60 mbar/min until 3 leakage points appeared (ie, 3 droplets formed) on its surface. The higher the pressure achieved before the appearance of the third water droplet on the fabric surface, the higher the water resistance of the specimen. Thirteen specimens taken from each zone (chest and sleeve seams) were tested using 3 different challenge liquids. Seventy-eight AATCC 127 experiments (3 liquids × 2 regions × 13 replicates) were conducted with 3 challenges on each of the level 2 and level 3 continuous fabric regions and on the seams (Table 4), resulting in a total of 390 AATCC 127 experiments. Additional 390 AATCC 127 experiments were conducted for gowns without AAMI PB70 claims and coveralls.

In addition to the number of experiments conducted corresponding to each cell in the design, Table 4 shows the mean, standard error of the mean, and the standard deviation for the results of the AATCC 127 and AATCC 42 tests for both the continuous fabric and discontinuous fabric regions.

RESULTS AND DISCUSSION

Analysis on gowns with AAMI PB70 claims

The primary aim of this study centered on examining potential differences in the penetration properties among gown fabrics when different challenge liquids were used. The liquid challenge agent was set as the primary independent variable. Given the difference in protective properties between Level 2 and 3 gowns, AAMI PB70 level was also included as an independent variable. After verifying that the assumptions required to conduct an analysis of variance (ANOVA) were met, 4 full-factorial ANOVAs were performed in The International Business Machines (IBM) SPSS version 25. In all models, the challenge liquid and gown AAMI PB70 level were the primary independent variables. In model 1, AATCC 42 results on the continuous fabric region was the dependent variable. model 2 included AATCC 127 results on the continuous fabric region as the dependent variable. model 3 included AATCC 42 results on the gown seamed area as the dependent variable. Finally, model 4 included AATCC 127 results on the gown seamed area as the dependent variable.

In all the ANOVA models, each of the effects (ie, the main effect of challenge liquid, the main effect of AAMI level, and their interactions) was significant at the $P < .001$ level. The correlation coefficient, R^2, for each of the models suggested that a sizable portion of the variance in AATCC 42 and AATCC 127 results was explained by the independent variables included in the model: model 1, $R^2 = 0.99$, adjusted $R^2 = 0.99$; model 2, $R^2 = 0.77$, adjusted $R^2 = 0.76$; model 3, $R^2 = 0.93$, adjusted $R^2 = 0.93$; and model 4, $R^2 = 0.86$, adjusted $R^2 = 0.86$.

Main effects for AATCC 42models

Without considering the effect of the liquid agent, AAMI PB70 Level 3 gowns resulted in significantly lower AATCC 42 values (ie, better barrier resistance) on both the continuous fabric regions (Level 3, M = 5.80 g; Level 2, M = 7.90 g, $P < .001$) and discontinuous fabric regions (Level 3, M = 0.85 g; Level 2, M = 7.27 g, $P < .001$) than Level 2 gowns. On the continuous fabric region, without considering the gowns' AAMI PB70 levels, water (M = 0.31 g) resulted in significantly lower AATCC 42 values when compared to both the SBF (M = 17.99 g) and synthetic blood (M = 2.24 g), $P < .001$. This result could be attributed to the difference in the surface tension of these

Table 4
Descriptive statistics for gowns with ANSI/AAMI PB70 claims

Test	AAMI level	Agent	Fabric region	N	Mean	St. error	Standard deviation
AATCC 127 (cm H_2O)	Level 2	SBF	Continuous	39	18.08	0.56	3.51
			Seam	39	13.26	0.71	4.46
		Synthetic blood	Continuous	39	22.07	1.18	7.40
			Seam	39	17.79	0.81	5.04
		Water	Continuous	39	34.84	1.14	7.12
			Seam	39	30.01	0.83	5.18
	Level 3	SBF	Continuous	26	27.31	0.41	2.09
			Seam	26	25.36	0.71	3.64
		Synthetic blood	Continuous	26	30.18	2.07	10.58
			Seam	26	26.90	1.48	7.53
		Water	Continuous	26	65.86	2.87	14.65
			Seam	26	58.38	1.48	7.57
AATCC 42 (g)	Level 2	SBF	Continuous	39	19.14	0.11	0.66
			Seam	39	18.00	0.12	0.77
		Synthetic blood	Continuous	9	4.08	0.73	2.18
			Seam	9	2.91	0.54	1.62
		Water	Continuous	39	0.48	0.06	0.35
			Seam	39	0.89	0.46	2.87
	Level 3	SBF	Continuous	26	16.85	0.19	0.98
			Seam	26	2.47	0.64	3.27
		Synthetic blood	Continuous	6	0.40	0.33	0.80
			Seam	6	0.03	0.02	0.06
		Water	Continuous	26	0.13	0.05	0.27
			Seam	26	0.06	0.01	0.02

AAMI, Association for the Advancement of Medical Instrumentation; *AATCC*, American Association of Textile Chemists and Colorists; *ANSI/AAMI*, American National Standards Institute/Association for the Advancement of Medical Instrumentation; *SBF*, simulated body fluid.

challenge liquids. Results associated with the SBF also significantly differed from those of synthetic blood, $P < .001$. On the gowns' seamed areas, penetration of water (M = 0.48 g) was also significantly lower (at the $P < .001$ level) than the SBF (M = 10.24 g). Penetration of synthetic blood (M = 1.46 g) was not different from water ($P = .11$), but was significantly lower than fabrics' penetration of the SBF ($P < .001$).

Main effects for AATCC 127models

Without considering the effect of liquid agent, AAMI PB70 Level 3 gowns resulted in significantly higher AATCC 127 values (ie, better barrier resistance) on both the continuous fabrics (Level 3, M = 41.12 cm H_2O; Level 2, M = 24.99 cm H_2O, $P < .001$) and in the seams (Level 3, M = 36.88 cm H_2O; Level 2, M = 20.35 cm H_2O, $P < .001$) than Level 2 gowns. This was due to difference between the fabrics used in the construction of AAMI PB70 Level 2 and 3 gowns and AAMI PB70 classification requirements (minimum 20 cm H_2O vs 50 cm H_2O for Level 2 and 3 gowns, respectively). On the continuous fabric regions, without considering the gown's AAMI PB70 level, water resulted in significantly higher AATCC 127 values (M = 50.35 cm H_2O) when compared to both the SBF (M = 22.70 cm H_2O) and synthetic blood (M = 26.12 cm H_2O), $P < .001$. This result could be attributed to the higher surface tension of water compared to that of both SBF and synthetic blood, which was expected to result in a higher barrier resistance. SBF also significantly differed from synthetic blood ($P = .02$), meaning that gowns provided more resistance to the penetration of synthetic blood than SBF, most probably due to the lower surface tension of the SBF compared to synthetic blood. Similarly, on the gown's seams, water (M = 44.20 cm H_2O) was significantly higher (at the $P < .001$ level) than both SBF (M = 19.31 cm H_2O) and synthetic blood (M = 22.35 cm H_2O), and SBF was significantly different from synthetic blood ($P = .003$). These results closely match with the declining pattern of surface tension from water to synthetic blood to SBF. As seen, the differences in the AATCC 127 results with water and synthetic blood are larger in comparison to the differences in the AATCC 42 results with water and synthetic blood. This may be attributed to the differences in the test methods. Similar patterns were also observed in earlier studies with several methods.[9,12]

Interaction effects for AATCC 42 and AATCC 127

Figures 1 and 2 show the significant interactions for each of the ANOVAs modeled. Figure 1 shows the significant interaction between the challenge liquid and AAMI PB70 level on the continuous and seam fabric regions for AATCC 42 (F = 37.37, d.f. = 2, $P < .001$ and F = 197.86, d.f. = 2, $P < .001$, respectively). Figure 2 depicts the significant interaction between the challenge liquid and AAMI PB70 level on the continuous and seam fabric regions for AATCC 127 (F = 38.62, d.f. = 2, $P < .001$ and F = 53.54, d.f. = 2, $P < .001$, respectively).

For each ANOVA individually, least significant difference adjusted, post hoc multiple comparisons were conducted to statistically compare the means for each challenge liquid for each AAMI PB70 level in a pairwise fashion.

In model 1 (Fig 1, left panel), each of the liquid agents statistically differed (at the $P < .001$ level) from the others when AATCC 42 tests were conducted on AAMI PB70 Level 2 gowns on the continuous fabric regions: the impact penetration resistance of fabrics with SBF was found to be M = 19.14 g, while that with synthetic blood was M = 4.08 g and that with water was M = 0.48 g. This demonstrates that the impact penetration resistance of gowns with water is higher compared to that with synthetic blood as well as SBF. It should be highlighted that AATCC 42 results with water and synthetic blood are closer to each other than the results with SBF. When tested with AAMI PB70 Level 3 gowns, the impact penetration of fabrics with SBF (M = 16.85 g) was significantly different from that with both water (M = 0.13 g) and synthetic blood (M = 0.40 g). The difference between synthetic blood and water was not statistically significant ($P = .46$). A similar but clearer pattern was observed with Level 3 gowns, since differences in the results when conducted with water and synthetic blood were not found significant. Importantly, although AAMI PB70 Level 2 and Level 3 gowns allow less than 0.5 g of water through when 500 ml of water is sprayed, more than 16 g of a liquid with a lower surface tension can penetrate, potentially including some body fluids. If the same requirements applied for the other challenge liquids for AAMI PB70 classification, only the 11G gowns would pass with the specified levels. As will be shown subsequently, 11G does not meet the AATCC 127 requirements of AAMI PB70 with these other challenges. McCullough's study[9] also reported higher AATCC 42 impact penetration values with challenges of low surface tension and higher resistance values with challenges of high surface tension. These findings also support Jaques et al.'s[26] findings, although their applied test method is different from the one used in this paper.

In reference to model 2 (Fig 2, left panel), each of the liquid agents statistically differed (at the $P < .05$ level) from the other when AATCC 127 tests were conducted on AAMI PB70 Level 2 gowns on the continuous fabric regions: SBF, M = 18.08 cm H2O; synthetic blood, M = 22.07 cm H_2O; water, M = 34.84 cm H_2O. When tested with AAMI PB70 Level 3 gowns, the results with water (M = 65.86 cm

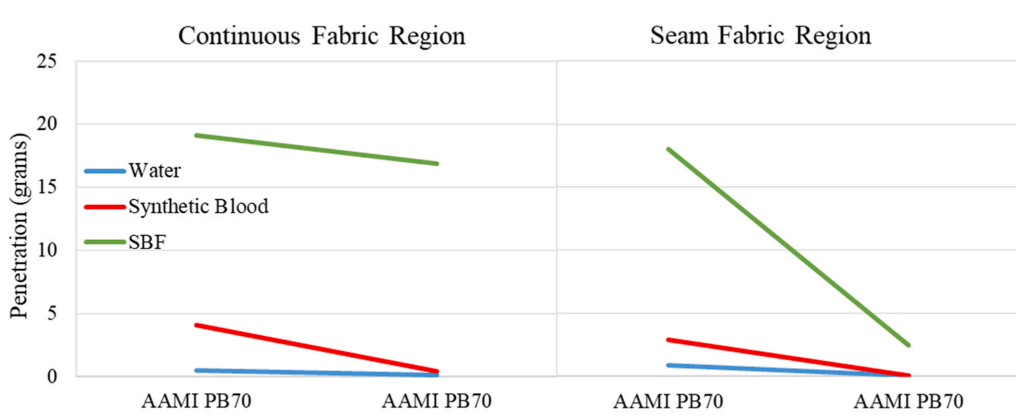

Fig. 1. Marginal means of American Association of Textile Chemists and Colorists (AATCC) 42 liquid penetration on the continuous and seam fabric regions by the liquid agent for gowns with Association for the Advancement of Medical Instrumentation (AAMI) PB70 claims.

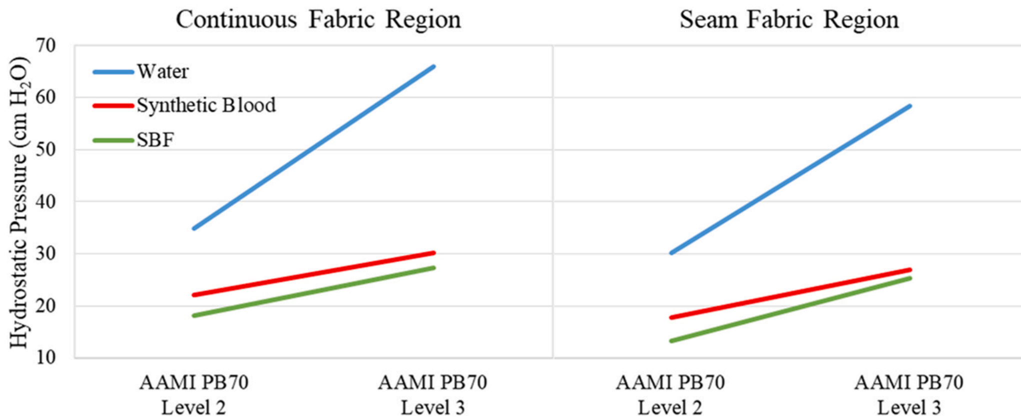

Fig. 2. Marginal means of American Association of Textile Chemists and Colorists (AATCC) 127 liquid penetration on the continuous and seam fabric regions by the liquid agent for gowns with Association for the Advancement of Medical Instrumentation (AAMI) PB70 claims.

H_2O) were significantly different from those with both SBF (M = 27.31 cm H_2O) and synthetic blood (M = 30.18 cm H_2O). Results with synthetic blood and SBF were not significantly different (P = .21). More SBF penetrated the fabrics than synthetic blood and water. Although the gowns provide some resistance to water, their penetration resistance significantly decreased with the decreasing levels of surface tension; that is, the results correspond with the relative values of surface tension of the 3 liquids. The results also show that the hydrostatic resistance values of fabrics to SBF and synthetic blood are closer to each other and lower than those to water. McCullough et al.[9] (1992) found that the liquid with low surface tension (70% isopropyl alcohol with 0.022 N/m surface tension) provides the lowest AATCC 127 resistance to penetration results, while the test results showed an increasing trend when conducted with liquids with higher surface tension (ie, synthetic blood (0.042 N/m) and distilled water (0.069 N/m)). These findings support Jaques et al.'s[26] findings, although their applied test method was different from the one used in the current study. It should be highlighted that while the results of SBF and synthetic blood are closer to each other and very different from the test results with water for AATCC 127 tests, with AATCC 42 tests the results with synthetic blood and water are close to each other and much different from the results with SBF. These AATCC 42 results also align with the findings of Mackintosh et al.[12] with fabrics made of synthetic fibers (such as Tyvek)[12] and 3 challenges (water, 0.066 N/m; serum-fetal or newborn calf, 0.050 N/m; and a solvent, 0.022 N/m) using another penetration testing method. These findings could be explained by the difference in the testing techniques as well as the droplet size and surface tension difference of the challenge liquids. A gradual continuous pressure by liquid is applied on the fabric surface in AATCC 127 testing, while impact pressures generated by sprayed liquids from a fixed distance in the AATCC 42 test can create different values due to the varying sizes of droplets. Additionally, surface tension and viscosity differences will create different droplet sizes throughout the spraying.

In model 3 (Fig 1, right panel), each of the liquid agents statistically differed (at the P < .01 level) from the other when AATCC 42 tests were conducted on AAMI PB70 Level 2 gowns on the seam regions: SBF, M = 18.00 g; synthetic blood, M = 2.91 g; water, M = 0.89 g. When tested with AAMI PB70 Level 3 gowns, SBF (M = 2.47 g) was significantly different from both water (M = 0.06 g) and synthetic blood (M = 0.03 g). Similar to model 2 results on the continuous regions, synthetic blood and water were not significantly different (P = .97). As seen from the results, although AAMI PB70 Level 2 and Level 3 gowns' seamed areas can achieve less than 1 g of penetration of water, they can permit more (2.47-18 g) fluid when exposed to a liquid with a lower surface tension, similar to some of the body fluids.

In reference to model 4 (Fig 2, right panel), penetration resistance results with each of the challenge liquids statistically differed (at the P < .001 level) from the other when AATCC 127 tests were conducted on AAMI PB70 Level 2 gowns on the seam regions of the gowns: SBF, M = 13.26 cm H_2O; synthetic blood, M = 17.79 cm H_2O; water, M = 30.01 cm H_2O. When AAMI PB70 Level 3 gowns were tested with water, the result (M = 58.38 cm H_2O) was significantly different from those with both SBF (M = 25.36 cm H_2O) and synthetic blood (M = 26.90 cm H_2O). Synthetic blood and SBF were not significantly different (P = .32).

Analysis on protective clothing without AAMI PB70 claims

In addition to the analysis on gowns with AAMI PB70 claims, 3 protective clothing models (a gown and 2 coveralls) without AAMI PB70 claims were examined using the AATCC 127 test. Differences in AATCC 127 hydrostatic pressure (cm H_2O) were examined through ANOVA with gown ID (1C, 2C, and 2G) and the challenge liquid (water, SBF, and synthetic blood) as the independent variables. Table 5 shows the number of experiments, the mean hydrostatic pressure, standard error of the mean, and standard deviation for each gown by liquid agent. The main effects of agent and gown identification were both significant (F = 78.92, P < .001 and F = 2062.70, P < .001, respectively). The two-way interaction was also significant, F = 33.29, P < .001. Figure 3 plots the significant two-way interaction.

Follow-up pairwise comparisons were used to examine the differences in the challenge liquid within each individual gown. For coverall 1C, the mean AATCC 127 hydrostatic pressure for SBF (M = 368.20 cm H_2O) was significantly different from that for both synthetic blood (M = 508.68 cm H_2O) and water (M = 507.19 cm H_2O), while the hydrostatic pressures for both synthetic blood and water were not significantly different from one another. For gown 2C, hydrostatic pressures with each of the liquid agents were significantly different from one another: SBF, M = 47.21 cm H_2O; synthetic blood, M = 83.81 cm H_2O; and water, M = 114.28 cm H_2O. For gown 2G, none of the liquid agents were significantly different: SBF, M = 253.68 cm H_2O; synthetic blood, M = 256.81 cm H_2O; and water, M = 251.57 cm H_2O. This result may be attributed to the structure of the gown fabric. Gown 2G has a laminated structure; therefore, when the film laminated on the outside of the gown fabric comes into contact with the liquid, the surface tension of the gown does not significantly affect the penetration properties, and failure occurs when the liquid bursts to the ruptured fabric surface due to bulging. A similar result was also observed with gown 3G, which is made of polyethylene film. AATCC 127 values with SBF, synthetic blood, and water were

Table 5
Descriptive statistics for protective clothing without AAMI PB70 claims

Gown ID	Agent	Mean AATCC 127 on continuous fabric (cm H_2O)	N	Std. error of mean	Std. deviation
1C	SBF	368.20	13	19.64	70.80
	Synthetic blood	508.68	13	1.18	4.24
	Water	507.19	13	1.82	6.56
2C	SBF	47.21	13	0.84	3.03
	Synthetic blood	83.81	13	0.89	3.22
	Water	114.28	13	2.29	8.24
2G	SBF	253.67	13	4.97	17.92
	Synthetic blood	256.81	13	4.74	17.10
	Water	251.56	13	5.36	19.32

AAMI, Association for the Advancement of Medical Instrumentation; *AATCC*, American Association of Textile Chemists and Colorists; *SBF*, simulated body fluid.

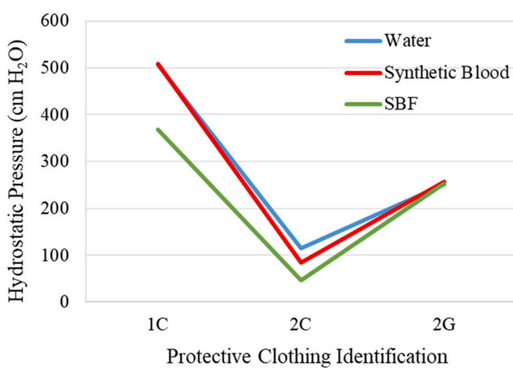

Fig. 3. Marginal means of American Association of Textile Chemists and Colorists (AATCC) 127 liquid penetration on the continuous fabric region by liquid agent for gowns without Association for the Advancement of Medical Instrumentation (AAMI) PB70 claims.

measured as 72.7, 74.4, and 75.1 cm H_2O, respectively, for 3G. The differences in the values could be attributed to the strength of the film rather than the surface tension of the liquid, as intact films do not allow measurable penetration and therefore AATCC 127 measures the breakout point of the structure. AATCC 42 values of 1C, 2C, 2G, and 3G were all-reported as "0 g" as no penetration occurred, as expected.

The other gown without an AAMI PB70 claim that was tested with different liquids using AATCC 42 and AATCC 127 was 13G. The gown, made of a very thin spunbond polypropylene fabric, was included in the set due to wide range of use of light nonwoven gowns in hospital settings. However, it was not added to the statistical analysis as the differences in structure from the rest of the gown or coverall models was expected to skew the analysis. For the 13G model, AATCC 127 values with SBF, synthetic blood, and water were reported as 4.5, 6.6, and 7.1 cm H_2O, respectively. AATCC 42 values with SBF, synthetic blood, and water were reported as 20.8, 17.3, and 24.6 g, respectively. As seen, the decreasing pattern of the liquid barrier resistance with decreasing surface tension was not seen in the AATCC 42 test result. A similar unexpected result was found in an earlier study[12] with 3 liquids when a highly hydrophilic fabric (cotton) was used. Although penetration was very rapid with the fabrics containing cotton, the rate of penetration by the serum was slower than that found for plain water. Mackintosh et al. explained[12] this as a consequence of adsorption and clotting of the serum on the cotton fibers. The difference in the trend could be also attributed to the difference in the test methods, as AATCC 42 measures the impact pressure. Also, this result could stem from the differences in droplet size and pressure applied. This result is also in alignment with McCullough's findings[9]. Further analysis was conducted on 13G composition with gas chromatography–mass spectrometry as the images taken with scanning electron microscopy revealed a coating on the fabric surface. The results showed that isopropyl palmitate was present as a finish on 13G. Isopropyl palmitate is an ester formed from isopropyl alcohol and palmitic acid and often used as an antistatic agent. It can also increase the barrier resistance properties. Since 13G fabric has limited strength, to be able to investigate its barrier properties, the AATCC 42 test was conducted with a metal mesh structure providing support. The mesh (McMaster-Carr-304 Stainless Steel Wire Cloth) used for the study was a woven structure with metal wires (wire diameter: 0.05334 mm) and with 0.07366 mm opening size and 34% open area. The AATCC 42 test was conducted by just using the metal mesh, and the reported values with SBF, synthetic blood, and water were 21.91, 20.45, and 22.7 g, respectively. These results paralleled the results with the fabric and showed that the fabric had a minimal resistance to penetration of synthetic blood and SBF, and that interactions between the fabric and water result in high penetration values.

Correlation analysis

Pearson correlation analysis was conducted to understand the relationship between the contact angle, air permeability, and penetration test results. When continuous regions of Level 2 and Level 3 gowns were tested, it was found that there is a significant correlation between air permeability and barrier resistance regardless of the challenge liquid used for the AATCC 42 impact penetration test ($P < .01$). Therefore, when an open structure is used for the fabric construction, the liquid can penetrate easily. However, the relationship between the contact angle and AATCC 42 results was only significant for synthetic blood (correlation coefficient = −0.748, $P < .01$). Since the AATCC 42 test is conducted with a continuous liquid flow, the contact angle becomes less important for fabrics' resistance to the penetration.

When AATCC 127 test results were considered, air permeability and hydrostatic resistance values were found to be negatively correlated, as expected ($P < .01$). While a significant positive correlation was found between the contact angle and AATCC 127 test results for synthetic blood and water ($P < .01$), the relationship was significant ($P < .05$) but negative for the AATCC 127 results with SBF. Since the AATCC 127 test is conducted by continuous contact with the liquid, the contact angle becomes less important for fabrics' resistance to the penetration.

Also, regardless of the liquid used, there was a significant relationship between the fabric weight, fabric thickness, and AATCC 42 and AATCC 127 values, as expected.

CONCLUSIONS

In health care settings, the primary purpose of protective garments is to protect HCWs from microorganism penetration. In operating theaters, body fluids and other liquid carriers, such as alcohol and iodine, may transport microbiological contamination through PPE fabrics. Thus, it is important to consider the barrier effectiveness of these fabrics to prevent the transmission of infectious pathogens.

Although the current standard test methods use only water for categorizing minimal to moderate barrier performance gowns for liquid penetration resistance, the findings presented in this study suggest that there is a significant difference in the penetration performance of protective clothing when exposed to other liquid challenges, including synthetic blood. Overall, gowns with AAMI PB70 Level 3 claims provided better barrier resistance against all the 3 liquid challenges compared to gowns with AAMI PB70 Level 2 claims. In general, the barrier resistance of protective clothing decreased with the decreasing surface tension values of liquid challenges, with some exceptions. Continuous areas of one of the coveralls (1C) provided the highest amount of protection from liquid penetration on the tests performed in this study with 3 challenge liquids, followed by a laminated nonwoven gown (2G). The light isolation gown constructed of a single fabric layer resulted in the highest penetration regardless of the challenge liquid used. Among the gowns without AAMI PB70 claims, a film gown also showed high penetration resistance to all the challenge liquids, as did a coated nonwoven coverall (1C) and a laminated nonwoven gown (2G). The other coverall (2C) provided higher penetration resistance to water and synthetic blood, and the penetration resistance was immensely reduced when tested with a liquid with reduced surface tension. Among AAMI PB70 Level 2 and 3 gowns, water produced the highest penetration resistance for all gowns and all test methods. In general, synthetic blood yielded penetration levels between water and SBF. The results of the current study show that the tested fabrics consistently resisted water penetration but were susceptible to penetration with low-surface-tension challenge liquids. When the impact penetration and hydrostatic pressure test results of each of the AAMI Level 2 and 3 gowns with synthetic blood and SBF were compared with the AAMI PB70 testing requirements with water, none of the gowns could achieve AAMI PB70 performance requirements. Due to the reported stability issues with the surface tension, cost, and difficulties of working with synthetic blood, a liquid with reduced surface tension could be used to simulate the surface tension of body fluids. A red dye could be also added to increase the visibility of solvents. Among the tested liquids, distilled water and liquids with reduced surface tension (SBF) are less expensive and more readily available; however, strikethrough may be easier to visualize with synthetic blood.

The limitations of the study include the type of surfactant and viscosity of the fluid used. Selection of the surfactant could be important, as the differences in chemical and molecular properties of the surfactants may lead to different results. Additionally, viscosity may also affect the wetting and penetration characteristics of fluids.

The findings highlight that when selecting an appropriate garment for the required tasks, safety professionals and those who select and/or wear the PPE should consider the varying barrier performances of protective clothing with different liquids and the use limitations. Furthermore, standard development organizations should consider multiple challenge liquids when classifying protective clothing for health care settings.

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH, CDC.

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