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Development of plasma enhanced antiviral surgical gown for healthcare workers

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Abstract

Plasma treatments are gaining popularity in the textile industry due to their numerous advantages over conventional wet processing techniques. In this study, nonwoven fabrics spunbond polypropylene, polyester basis weight of 25 g/m^2 and microporous PTFE film were used to develop tri-laminate antiviral surgical gown. The outer layer of spunbond polypropylene was treated with plasma enhanced fluorocarbon. The plasma treated polypropylene was also treated with titanium nano dispersion finish in a single bath pad-dry-cure method. The pore sizes of nonwoven fabrics were characterized using tri-nocular microscope. The titanium nano finished polypropylene was characterized by scanning electron microscope. The tri-laminate surgical gown was developed with outer layer of plasma treated polypropylene, middle layer of PTFE and inner layer of polyester nonwoven. Liquid barrier properties of surgical performance were analyzed by viral penetration, antibacterial, spray impact penetration, hydrostatic resistance, tensile properties and moisture vapour permeability to estimate their suitability for antiviral surgical gown. It is observed that plasma treated gown shows 99.04% bacterial reduction as compared to untreated, thus providing barrier against microbes. The plasma treatment does not alter the weight and tensile properties of surgical gown. The developed plasma enhanced flurocarbon treated tri-laminate surgical gown offer sufficient liquid barrier properties for level 4 protection as per Association for the Advancement of Medical Instrumentation classification. Moisture vapour transfer rate of plasma treated tri-laminate gown decreased by 21% in comparison with untreated nonwoven gown.

Keywords: Viral penetration; Hydrostatic; Moisture vapour; Impact penetration; Antibacterial

Introduction

Surgical gown should be made out of liquid proof fabric to protect the blood-borne infectious microbes from penetrating through the fabric. Risks of patients are contamination from both endogenous and exogenous microorganisms and risk of healthcare workers are contamination from various blood-borne pathogens due to occupational exposure to patient blood and body fluids (Unsal et al. 2005). Surgical gowns should provide an effective protective barrier against the transfer of microorganisms, particulates and fluids, in addition to acting as an aseptic barrier for the patient's protection, in order to minimize strike-through and the potential for personnel contamination (Rutala and Weber 2001). Due to the prevalence of HIV and hepatitis B and C viruses in the patient population, the barrier efficacy of protective surgical gowns have gained importance. During surgery, in an operating room, a patient's blood can penetrate surgical gown material and possibly contaminate the surgeon's skin, if not well protected. Several blood borne pathogens have the potential to spread in this manner, the most important being the HIV and the hepatitis B virus, which are related to AIDS and hepatitis (Loveday et al. 2007).

Surgical gown materials should have antimicrobial properties and blood repellency properties in order to protect patients from contamination by surgical staff during operations and also to protect the surgical team from infectious blood and other body fluids (Mews 2009). Commercial available polyester, polyester-cotton and cotton plain woven fabrics were treated with fluropolymer and found that polyester and cotton twill fabrics have high protection (Midha et al. 2014). To apply both antimicrobial and flurochemical repellent finishes to nonwoven surgical gown fabrics, a one-bath process was investigated by Huang and Karen (2007). Etching of fabrics with functional groups from a gas based plasma treatment can impart functionality, such as grafting polar surface groups to impart hydrophilicity on a hydrophobic fibre surface. There have even been studies conducted on greige fabric treated with plasma and research was made to allow greige fabric to be dyed without the requirement of fabric preparation such as desizing, scouring, and bleaching. The research found that exposing a greige fabric to plasma altered the surface so that it became hydrophilic. Through the formation of polar groups on the fabric surface, during plasma treatment, the increas hydrophilicity was studied for use in pretreating textiles (Gawish et al. 2008; Rajpreet et al. 2004).

Flurochemical finishes, commonly referred to as flurocarbon finishes, are the most widely used repellent finish in the textile industry and both natural and synthetic fibres can be treated (Huang and Leonas 1999; Jessie et al. 2007). During laundering, dry cleaning, and tumble drying excellent chemical and thermal stability of flurocarbons allow them to have great durability. In addition, flurocarbon finishes can be applied at a lower add-on than any other repellent finishes (Tyner 2007). A new standard (ASTM F2407, Specification for Surgical Gowns Intended for Use in Healthcare Facilities) which facilitates the gown selection process was developed under the auspices of the American National Standards Institute (ANSI) and the Association for the Advancement of Medical Instrumentation (Association for the Advancement of Medical Instrumentation 2003) responded to these shortcomings. A barrier material's performance is classified into four levels by this standard. Table 1 shows Classification of barrier performance and the results of the following tests as per Association for the Advancement of Medical Instrumentation (AAMI).

This research work aims to develop plasma enhanced fluorocarbon treated surgical gown to protect the healthcare workers from pathogens spreading from patients as well

Table 1 Classification of barrier performance as per AAMI

AAMI barrier performance	Test	Result
Level 1	AATCC42:2000 Impact penetration test	≤4.5 g
Level 2	AATCC42:2000 Impact penetration test	≤1.0 g
	AATCC 127:1998 Hydrostatic pressure test	≥20 cm
Level 3	AATCC42:2000 Impact penetration test	≤1.0 g
	AATCC 127:1998 Hydrostatic pressure test	≥50 cm
Level 4	ASTM F1671:2003 Viral penetration test	Pass

as reverse contamination. Liquid barrier properties of surgical performance were analyzed by viral penetration, antibacterial, spray impact penetration, hydrostatic resistance, tensile properties and moisture vapour permeability.

Methods

Spun bond polypropylene and polyester nonwoven fabrics were obtained from Mogul nonwoven industry, Turkey. The diameter of the individual polypropylene filament was approximately 0.2 microns and diameter of the individual polyester filament was 0.8 microns. The basis weights of the both nonwoven fabrics were 25 grams per square meter. The prime components of this research are polypropylene and polyester nonwoven fabrics. As polypropylene fibre has stereo-regular isotactic molecular structure, due to its high degree of crystallinity, good handling, strength and a high enough melting point for normal use, it is being used in many industrial applications, as well as in healthcare protective clothing. It has non polar and hydrophobic nature which is a good liquid repellent property. Considering its liquid barrier protection PP nonwoven is used as an outer layer in the developed surgical gown. Polyester nonwoven fabric is used as an inner layer in the developed surgical gown because of its wickability characteristics. The wickability nature of polyester nonwoven transfer the moisture from inner to outer layer through capillary action which makes the wearer comfort.

Figure 1 shows the plasma experiments conducted on the samples. Prototype downstream Atmospheric Pressure Plasma Reactor is equipped with a controlled stage and a solid state power generator. The stage was cooled using a chiller. The monomer was

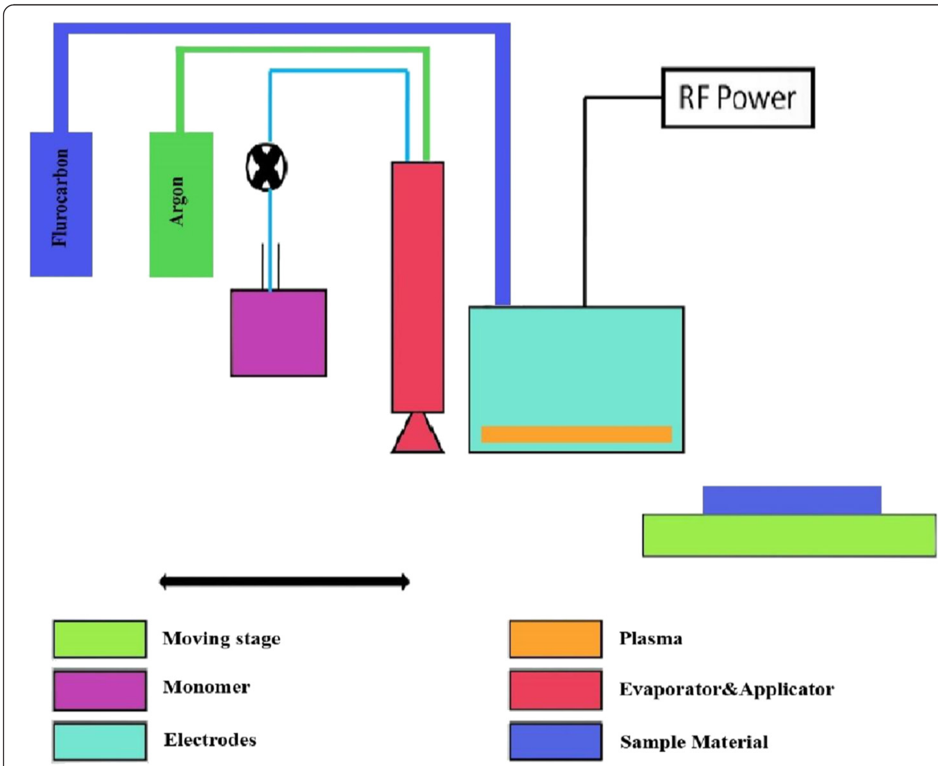

Figure 1 Plasma experiment setup.

pumped into a lab designed heated evaporator through an equipped tube. The fluorocarbon gas used to provide hydrophobicity was C_3F_6. The radio frequency required to build the electromagnetic field was 600 watts. The electrode applicator height was 3 mm. The flow rate monomer was maintained as 0.6 ml/min and the exposure time was 10 seconds.

Fabric was cut into 15 cm square samples. The samples were ironed to reduce wrinkling and to give an even surface height for treatment. Samples were then mounted on the stage using double sided sticky tape. Sample surface was made as smooth as possible, and loose yarns were removed or taped down. Once stable plasma was generated, stage was turned on to move sample into the plasma field for the desired exposure time for the pre-deposition surface activation treatment. After the sample passed out of the plasma field, it passed beneath the applicator, which deposited the monomer to condense and graft activated species on the fabric surface. Monomer flow was then turned off. Stage direction was reversed, and the sample passed through the plasma field for second time to induce free radical polymerization of the monomer on the fabric surface. Fabric sample was then removed from the stage and the treatment was done on both the sides.

A schematic of the flurocarbon plasma reaction mechanism is shown in Figure 2, in which I^+ refers to an ion, I^* refers to a hot neutrals, the dashed lines represent energy transfer through the polymer and the curved lines represent species diffusion through the polymer. Through the deposition of a flurocarbon as an overlayer, etching of surface proceeds. C_xF_y radicals are the precursors to polymerize deposition followed by ion activation of surface sites. The polymer layer is formed by energetic ion sputtering and F atom etching. The polymer layer is the main inhibitor for the transport of species and delivery of activation energy to the surface. The oxygen reacts with the flurocarbon species to release etch product such as COFx. Finally by this reaction lower surface energy to the polypropylene nonwoven surface was imparted.

For the application of synthesized Titanium nano dispersion, the most widely used method of application pad-dry-cure process was used. The plasma treated polypropylene nonwoven fabric was coated with 1% nano dispersion with material to liquor ratio of 1:20 and 0.5% anionic binder. The fabric samples were immersed in the bath followed by padding through squeezed rollers at a pressure of 147 N/cm^2 to remove the excess liquid. Each fabric sample was padded with the solution twice to ensure even distribution of solution. After padding, the fabric was dried naturally and then cured at 150°C for 2 min. The wet pick up was 89%. The add-on of the titanium nanoparticles was 87%. Pore size of the plasma enhanced nano finished outer nonwoven fabric was characterized using tri-nocular microscope.

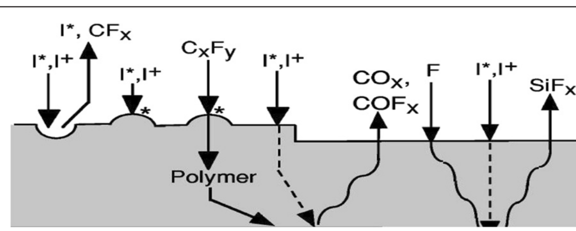

Figure 2 Flurocarbon plasma mechanism.

The plasma enhanced fluorocarbon treated fabric samples were characterized using scanning electron microscope. Tri-laminate gown with plasma enhanced flurocarbon treated nano finished polypropylene as an outer layer, PTFE film as a middle layer and polyester nonwoven fabric as an inner layer were bonded together using a fusing machine at a temperature of 165°C with pressure of 98 N/cm^2. The developed plasma treated surgical gown was tested and analyzed for the following properties such as Viral penetration analysis, antibacterial, tensile, Spray impact penetration, hydrostatic resistance and moisture vapour permeability.

Risks of healthcare workers are contamination from various blood-borne pathogens due to occupational exposure to patients' blood and body fluids. So the antibacterial testing was performed for the developed surgical gown. Light activate antibacterial mechanism which involves interaction with and transferring energy to oxygen so as to provide a source of an active or excited oxygen species known as singlet oxygen. Singlet oxygen is an activated form of the usual triplet state molecular oxygen. Upon exposure to normal light, the dyes used in the present invention generate singlet oxygen that kills microorganisms. Bacteria require less light though they are more sensitive to the singlet oxygen generated by the light activated dye. Surgical room illumination of about 2000 foot candles is more than sufficient. Test swatches of this plasma treated nonwoven were tested for microbiological kill by inoculating the swatches.

The antimicrobial substrate so made comprises of a light activatable singlet oxygen generating substance to inhibit the growth of bacteria selected from the group consisting of Staphylococcus aureus, Pseudomonas aeruginosa, Escherichia coli, Mycobacterium bovis, methicillin resistant Staphylococcus aureus and Proteus vulgaris. The bacterial concentration was 0.5%.

Swatches with a 0.5% concentration of bacteria were exposed to light of 2000 foot candles or dark for a given period of time. After exposure for the required time, the number of live bacteria remaining on the test swatches was determined. The log of the remaining live bacteria versus the exposure time to light of 2000 foot candles and dark were determined. After a suitable incubation, bacterial colonies were counted, percent kill calculated. Recovery procedure started with transfer of samples into a sterilized capped tube containing about a dozen 3 mm glass beads and 5 ml of sterile phosphate buffered saline. After sealing the cap, the tube was shaken vigorously for one minute and then placed for 30 seconds in a low intensity ultrasonic cleaning bath. One ml of the recovery fluid was also placed directly in a 100 mm Petri plate. For one to two days the plates were incubated at 30°C., until countable. The zero time counts recovered from the swatches were compared with the inoculum count. To obtain and average log zero time reading, all of the zero time contents were combined by averaging their base 10 logarithms. Log reduction was calculated as the difference between the samples and average zero time logarithms. Percent kill was calculated as $100(1- Log_{10})$.

Viral penetration testing of surgical gown using ASTM F 1671 was carried out to investigate the antiviral property. ASTM F1671 is the test method used to measure the resistance of materials used in protective clothing for penetration by blood borne pathogens, using bacteriophage under the condition of continuous liquid contact. The test system has been designed for measuring penetration of surrogate microbe for hepatitis B virus (HBV), hepatitis C virus (HCV) and HIV. The protective clothing materials to be tested are intended to provide protection against blood, body fluids and other potentially infectious materials. The surface tension range for blood and body fluids is approximately 42 – 60 dynes/cm. In order to simulate the wetting characteristics of blood and body fluids, the surface tension of the ΦX174 bacteriophage suspension is adjusted to approximate lower end of this surface tension range (42 dynes/cm).

The ΦX174 bacteriophage was selected as the most appropriate surrogate for the blood borne pathogens mentioned because it satisfies all of these criterias. The ΦX174 bacteriophage is a non-enveloped 25 – 27 nm virus (similarly to HCV, the smallest pathogen) with an icosahedral or nearly spherical morphology and excellent environmental stability. It is non-infectious to humans, has a limit of detection which approaches a single virus particle, grows rapidly, and can be cultivated to reach high titers similar to HBV (the most concentrated pathogen mentioned). Test samples are prepared by randomly cutting the protective clothing material into approximately 75×75 mm swatches. Test samples are exposed to approximately 60 ml of the ΦX174 bacteriophage suspension. At the conclusion of the test, the observed side of the test sample is rinsed with a sterile assay medium and then analyzed for the presence of the ΦX174 bacteriophage. Surgical protective clothing 'pass/fail' determinations are based on detection of penetration.

Results and discussions

Scanning Electron Microscope (SEM) analysis of plasma enhanced flurocarbon treated polypropylene nonwoven fabric

The SEM observation of untreated and treated samples as shown in Figures 3 and 4, showed small scale erosion and fragmentation surface, which can be seen as small particles. It was noticed that control sample had a smooth surface. Flurocarbon plasma treated polypropylene nonwoven showed some redeposited particles of flurocarbon etched away during plasma treatment, due to oxidation of polypropylene plasma induced free radical polymerization of the monomer. Riikka Vaananen et al. (2010) obtained similar results. They noticed that the control sample had a smooth surface and the plasma treated sample showed some redeposited particles.

Pore size characterization of plasma finished fabric

The average pore size diameter of the polypropylene plasma treated and untreated fabrics are presented in Table 2. The pore size of flurocarbon treated outer layer polypropylene nonwoven fabric is 0.25 μm. The inner layer polyester nonwoven fabric pore

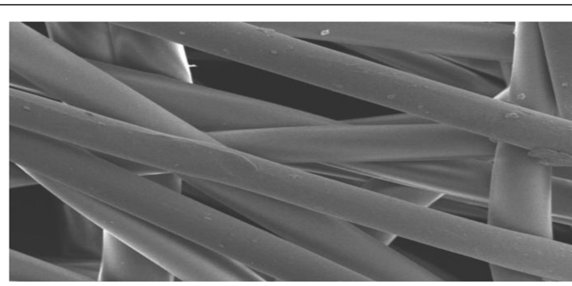

Figure 3 SEM image of untreated polypropylene.

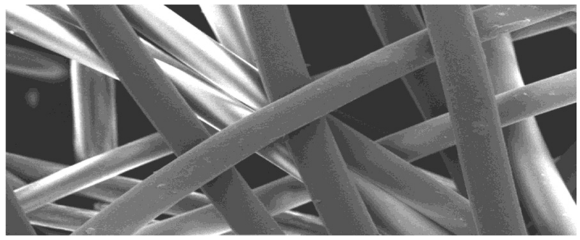

Figure 4 SEM image of plasma treated polypropylene.

size is 0.35 μm. The *t*-test p value (0.001) showed a significant difference in the mean pore diameter of untreated and plasma treated polypropylene nonwoven fabric.

A surface reaction mechanism of flurocarbon acrylate based repellents react through the C = C at the end of the chain. The electrons involved in the carbon-double bond-carbon are open to attack by a free radical. These free radicals are supplied by the plasma treatment, and exist on the activated fabric surface and are deposited following the monomer deposition. Once opened, free radical polymerization ensues. The graft polymerization occurs when the monomer reacts with a free radical on the surface of the fabric. The free radical attacks the double bond of the monomer, opening the bond and forming a new bond between the fabric and the monomer, through reaction which reduces the pore size of treated polypropylene nonwoven.

Viral penetration analysis

Table 3 shows the liquid barrier characteristics of the surgical gowns. The developed tri-laminate fabric with plasma treated polypropylene as an outer layer, PTFE film as a middle layer and polyester nonwoven fabric as an inner layer has passed the viral penetration test against the hepatitis B and hepatitis C, human Immunodeficiency viruses and surrogate ΦX174 bacteriophage. Plasma treated polypropylene single layer surgical gown failed the viral analysis due to the absence of PTFE film as it is not a barrier against viruses. The PTFE film is constructed from stretched polytetrafluroethylene which prevents the penetration of liquid but the interconnected pore structure allows the transmission of water vapor. PTFE film transports water molecules by molecular diffusion according to the sorption-diffusion model through the polymer matrix using difference in partial water-vapor pressure across the film as the driving force. Dual laminated flurocarbon treated polypropylene and polyester surgical gown failed in viral penetration analysis as it is observed that test liquid penetrated at the opposite of the fabric due to absence of PTFE film. In the absence of PTFE in the developed single layer plasma treated polypropylene gown, it also failed in the viral penetration analysis.

Table 2 Pore size of plasma enhanced flurocarbon treated nonwoven fabric

Nonwoven fabric	Pore size diameter (μm)	Maximum perimeter (μm)	Minimum perimeter (μm)
Untreated polypropylene	0.29	1.356	0.942
Plasma treated polypropylene	0.25	1.248	0.921
Polyester	0.35	1.471	0.985

Table 3 Viral penetration analysis of plasma enhanced flurocarbon treated gowns

S.No	Surgical gown	Viral penetration analysis
1	Plasma treated Polypropylene surgical gown	Fail
2	Plasma treated Polypropylene with PTFE dual layer surgical gown	Pass
3	Tri-laminate Plasma surgical gown	Pass
4	Dual laminated Plasma treated Polypropylene and polyester gown	Fail

Antibacterial activity

Table 4 shows the antibacterial log reduction and percentage reduction of microorganism in titanium nano composite flurocarbon finished polypropylene nonwoven fabric with exposure to light of 2000 foot candles and no light. When plasma is applied to the substrate, the free electrons break the chemical bonds, upon collision with substrate, creating free radical on the surface which influence adhesion of titanium nano composites. The graph in Figure 5 shows that there is a significant reduction in bacterial count and its average is 99.04% when exposed to light, whereas in zero time contact and no light, there is no reduction in bacterial count. The titanium nano dispersion photocatalytic activity kills bacteria, when it is illuminated by light with energy higher than its band gaps and the electrons in titanium dioxide jump from the valence bond to the conduction bond.

The flurocarbon treated polypropylene has slightly higher antibacterial resistance than untreated but it further enhances the property. The outer layer of polypropylene has control bacteria growth due to flurocarbon treatment. The current results are similar with the studies of Souma (2012), who observed that repellency is high for plasma treated sample and high concentration of flurocarbon is required to increase repellency.

Tensile and elongation of plasma enhanced flurocarbon treated surgical gown

Plasma treatment is a surface phenomenon and hence it should not significantly affect the tensile strength of nonwoven fabric. Research on atmospheric pressure plasma treated nonwovens shows that tensile properties are dependent on the severity of the treatment and the inherent properties of fabric such as the degree of entanglement of fibres, fibre-to-fibre frictional contact, laying of fibers in the web structure and the individual strength of fibers. Table 5 shows the results of tensile strength of the untreated and plasma treated fabrics. No significant changes were observed in results of tensile

Table 4 Antibacterial log reduction of plasma enhanced flurocarbon treated fabric

Samples			Bacterial count log value	
	Zero time	No light	Light (2000 fc)	% Antibacterial reduction
Control	2.4	2.3	2.3	24.20
Sample 1	2.4	2.3	1	98.94
Sample 2	2.4	2.4	0.9	99.08
Sample 3	2.4	2.4	0.9	99.08
Sample 4	2.4	2.3	1	98.94
Sample 5	2.4	2.3	0.9	99.08

Light: 2000 foot candels.
Time: 60 minutes.

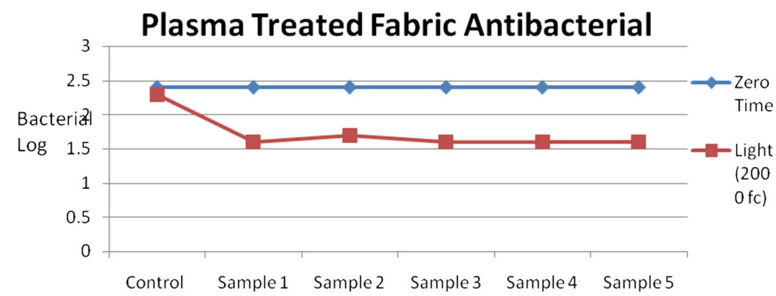

Figure 5 Plasma enhanced flurocarbon treated fabric antibacterial reduction.

strength after plasma treatment. Plasma treated fabric had only slight decrease in tensile strength wherever the fabric had higher energy per area.

The tensile strength of the tri-laminate gown in machine direction is greater than the cross direction of the sample as the laying of polypropylene fibre during extrusion is in the machine direction. Paired *t*-test analysis of the tensile strength in machine and cross direction shows that there is no significant difference at 95% confidence interval. This result is supported by findings of Vaananen et al. (2010). They reported that the plasma treated nonwoven fabric was lower in tensile strength of both machine and cross direction as compared to untreated nonwoven.

Impact penetration and hydrostatic resistance of plasma enhanced flurocarbon treated surgical gown

The impact penetration and hydrostatic resistance characteristics of untreated, plasma treated single layer polypropylene, dual laminate surgical gown and tri-laminate are shown in the Figure 6. It is observed that the weight of water penetrating through the fabric during impact penetration test decreases as the weight of fabric increases. The results are statistically significant for untreated fabric, plasma treated single layer, dual-laminate gown and tri-laminate gown at 95% confidence level. Application of plasma finish using flurocarbon reduces the surface energy of the fabric and does not permit the water or other fluids to absorb and spread on the fabric surface. Higher fabric weight offers more resistance to water penetration because of higher fabric thickness and more number of fibers per unit area of the fabric. More number of fibers per unit area lead to higher entanglements and compact fabric structure, resulting in the reduction of water penetration.

Table 5 Tensile and tearing strength of untreated and plasma enhanced flurocarbon treated surgical gown fabrics

Sample	Tensile strength (N)		Tearing strength (N)	
	MD	CD	DI	DII
Untreated Polypropylene (Single layer) surgical gown	105	62	10	5
Plasma treated Polypropylene (Single layer) surgical gown	98	54	7	3
Plasma treated Polypropylene with PTFE dual layer surgical gown	122	61	16	7
Tri-laminate Plasma surgical gown	149	74	21	13

MD - Machine direction, CD - Cross direction, DI - Direction 1, DII - Direction 2.

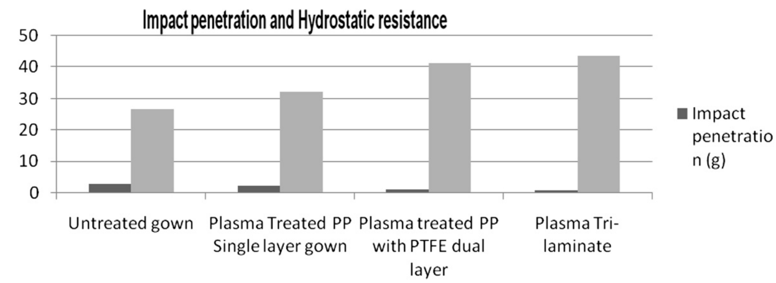

Figure 6 **Impact penetration and hydrostatic resistance of surgical gown.**

The hydrostatic resistance increases with increase in weight of the fabric in all gowns. The hydrostatic results are statistically significant for untreated nonwoven fabric, plasma treated single layer and dual layer fabrics at 95% confidence level. Plasma treatment with flurocarbon imparts lower surface energies to nonwoven fabric surface which increases resistance of treated fabric against blood. Dual layered of plasma treated polypropylene with PTFE gown offers better resistance than Single layer plasma treated polypropylene gown because of presence of PTFE.

According to the AAMI barrier performance classification, plasma treated tri-laminate surgical gown can be used for level 2 protection. The flurocarbon treatment makes the surface of fabric hydrophilic due to etching of fabric by deposition of a flurocarbon monomer following ion activation of surface sites. The polymer surface layer is the main inhibitor for developing repellency in nature. The present results are comparable with those of Rajpreet et al. (2004) who also performed hydrostatic resistance of flurocarbon treated nonwoven. Plasma treated nonwoven fabric is showing better hydrostatic resistance than untreated.

Moisture vapour permeability of plasma enhanced flurocarbon treated surgical gown

Moisture vapour transfer rate (MVTR) is the ability of a fabric to transfer perspiration in the form of moisture vapour through it. The MVTR of untreated and plasma treated sample were shown in Figure 7. MVTR of plasma treated tri-laminate gown decreased by 21% in comparison with untreated nonwoven gown. As the layer of nonwoven increases, water vapour permeability reduces. Moisture repellency is higher in flurocarbon treated nonwoven due to etching of fabric by deposition of a flurocarbon following ion activation of surface sites. The polymer surface layer is the main inhibitor for

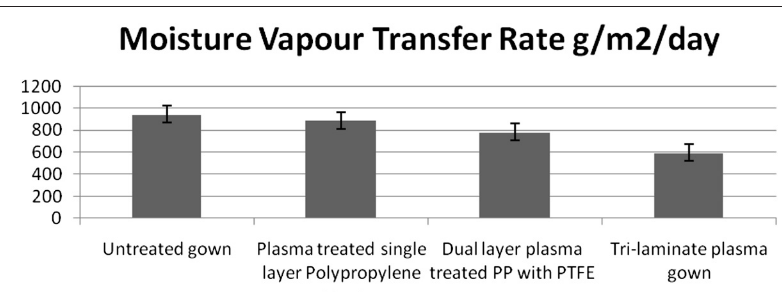

Figure 7 **Moisture vapour permeability of untreated and plasma enhanced flurocarbon treated surgical gown.**

developing repellency in nature. Hence the moisture vapour transfer of flurocarbon treated gown is lower as compared to other gowns. The study of Souma (2012) supports that the flurocarbon treatment improves repellency whereas reduces the moisture vapour transfer of nonwoven fabric.

Test of significance of means using paired *t*-test showed that the means of plasma treated and untreated fabrics were significantly different at 95% confidence interval. A negative correlation between the water vapour permeability against the increasing thickness of fabric has also been noticed. The regression equations as $Y = -986.36\times + 1139.09$.

Conclusions

Plasma enhanced fluorocarbon treated single, dual and tri-laminate surgical gowns have been used to study their suitability for antiviral surgical gowns. Pore size of plasma treated polypropylene nonwoven is smaller than untreated polypropylene, thereby influencing antibacterial resistance. Both the tri-laminate and dual layer plasma treated PTFE gowns passed in viral penetration analysis whereas plasma treated single layer surgical gown and dual laminated plasma polypropylene with polyester failed in viral penetration analysis due to absence of PTFE film. Impact penetration of Plasma treated single and dual layer gown offers level 1 protection and plasma tri-laminate gown has level 2 protection. Hydrostatic resistance of plasma treated tri-laminate gown offers level 2 protection. Tri-laminate plasma gown has better impact and hydrostatic resistance as compared single and dual laminate gowns. MVTR of plasma treated tri-laminate gown decreased by 21% in comparison with untreated nonwoven gown. The developed plasma enhanced fluorocarbon treated surgical confirms level 4 protection according to AAMI barrier classifications.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
VP has contributed design and development of study and analysis of data. GT has carried out testing of samples. All authors read and approved the final manuscript.

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