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Original Article

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Skin Barrier Impairment due to the Occlusive Effect of Firefighter Clothing

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Abstract

At fire scenes, firefighters are exposed to potentially harmful substances. Besides inhalation of these products, also skin contamination and the risk of dermal absorption is getting more attention. In this perspective, skin barrier impairment due to the occlusive effect of firefighter clothes could enhance the risk of penetration of hazardous substances. The effect of a firefighter jacket and cellophane on the skin was studied in a paired comparison involving 16 volunteers. Biophysical parameters were measured before, immediately after and 30 min after ending the occlusion. Reflectance confocal microscopy was used to study the skin morphology. Immediately after wearing a firefighter jacket, Transepidermal Water Loss values were significantly increased. This is an indication of an occlusive effect of the firefighter jacket. The skin barrier was fully restored after 30 min after occlusion with cellophane or wearing a firefighter jacket.

Keywords: barrier function; occlusion; personal protective equipment; skin

Introduction

At fire scenes, firefighters are exposed to various potentially harmful substances (Brandt-Rauf *et al.*, 1988). Especially the risk of toxic or even carcinogenic substances in smoke gets lots of attention, because of the potentially increased incidence of cancer among firemen (LeMasters *et al.*, 2006; Jahnke *et al.*, 2012; Anderson *et al.*, 2017; Casjens *et al.*, 2019; Jalilian *et al.*, 2019). To reduce work-related risks, Personal Protective Equipment (PPE) are used. Besides wearing the equipment, firefighters are trained to reduce contamination risk while handling (severely) contaminated gear and to use appropriate gear-cleaning protocols (Fent *et al.*, 2017; Harrison *et al.*, 2017).

Even when wearing suitable PPE, postfirefighting studies showed increased biomarkers of carcinogenic combustion products in their bodies (Fent *et al.*, 2014; Stec *et al.*, 2018). In general, inhalation, oral and skin penetration are considered as potential absorption mechanism of contaminants (Ogg *et al.*, 2012). While chemical exposures encountered during firefighting are thought to contribute to the elevated risk of cancer, the role that contamination on the PPE and the skin plays in this risk has not been well defined (Fent *et al.*, 2017). Let alone the influence the PPE has on the skin.

With its ingenious multilayered composition, the skin provides protection against chemical permeation. The outermost layer of the skin, the stratum corneum (SC), has due its tightly packed structure a 10 000 times higher resistance to diffusion than the lower layers (Agache, 2004). The skin barrier therefore is physically located in this layer. Maintaining an intact skin barrier is very important, to avoid infections and to limit the effect of (chemical) substances that should not enter the human body. Note, the skin barrier function can for example be reduced by mechanical skin damage, exposure to chemicals, irritants, and allergens. Also, normal intraindividual differences in the robustness of the skin barrier function and preexisting comorbidities (such as atopic dermatitis) make some individuals more susceptible to health effects than others, despite identical exposures. Accept for skin cancers, no specific references to dermatitis or deviant skin conditions in firefighters are known (Guidotti, 2014). Skin disorders, like dermatitis, are rare as causes of death. Which is the main reason they are almost never studied for occupational associations. Although there exist a certain lack of consistency in research papers, on balance there is a positive association between firefighting and skin cancer, probably in the order of 1.3–1.4 (Graveling and Crawford, 2010).

Whereas mechanical skin damage and the skin-damaging effect of detergents have been verified in numerous experimental and field studies, the impact of occlusion is more complex (Tiedemann *et al.*, 2016). Thus, the occlusive effect of carrying gloves may for instance influence the skin temperature, hydration, and pH. On the other hand, occlusion has also been reported to accelerate the healing of certain defects in the barrier. From studies on waterproof disposable diapers it is shown that skin permeability, CO_2 emission, frictional trauma, and growth of pathogenic micro-organisms are increased as skin hydration increases and the skin's barrier properties are compromised (Zimmerer *et al.*, 1986; Zhai and Maibach, 2002; Tate and Wright, 2017).

From literature it is shown that occlusion can block the diffusional water loss from skin surface, thereby increasing SC hydration, swelling the corneocytes, and promoting water uptake into intercellular lipid domains and hence compromises the skin barrier function (Zhai and Maibach, 2002). It is generally assumed that skin occlusion increases percutaneous absorption of chemicals (Zhai and Maibach, 2001).

Placing garment fabric over the skin does not usually create nearly an occlusive environment that results from the wearing of diapers or gloves (Hatch and Maibach, 2004; Tiedemann *et al.*, 2016). However, placing any garment fabric on the skin has the potential to change skin properties. Due to the coated multilayered construction and the use of a water-resistant membrane the breathability of firefighters' garment is significant lower than a non-coated single fabric (Hunter, 2009). The possible occlusive effect of the firefighters' garment might cause skin barrier impairment. This could lead to enhanced penetration of the hazardous substances. Unfortunately, now there is no quantitative data available in literature that gives an indication of a possible occluding effect of firefighters' clothing. Therefore, the objective of this study is to quantitatively investigate whether skin barrier impairment occurs when wearing firemen jacket which is an important trigger for enhancement of percutaneous penetration.

Methods

Experimental setup

The effect of wearing a firefighter jacket on the skin was investigated *in vivo* in healthy volunteers. The results were compared to the occlusive effects of cellophane foil in the same volunteers. The firefighter jacket consisted of fire resistant 100% aramid antistatic fabric (220 g m^{-2}) on the outside and a water-resistant membrane as lining (Fig. 1).

Various noninvasive techniques have been utilized to quantify the skin barrier function. In their review, Zhai and Maibach (2002) showed that Transepidermal Water Loss (TEWL) and capacitance as a parameter of SC hydration are good makers of the barrier function and structural changes of the skin and recovery of the barrier function. The noninvasive biophysical parameters which were used as readout in this study are summarized in Table 1.

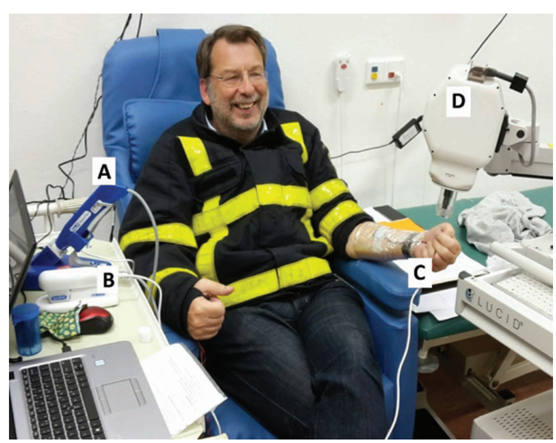

Figure 1. Experimental setup: TEWL and SSWL measurement (A), permittivity measurement (B), humidity and temperature sensor to monitor the occluded environment (C), and RCM (D).

Table 1. Overview of the measured biophysical parameters.

Physical parameter	Apparatus	Description
TEWL	BIOX AquaFlux, Biox Systems Ltd, England	Quantity of water crossing the SC eliminating sweating
SSWL	BIOX AquaFlux, Biox Systems Ltd, England	The amount of surface water present on the skin
Permittivity of the skin	Epsilon Model E100, Biox Systems Ltd, England	Capacitive measurement which correlates with the amount of hydration of the SC

Also reflectance confocal microscopy (RCM) was applied to study the morphology of the skin, respectively the SC thickness and viable epidermis thickness including the SC thickness (Falcone *et al.*, 2015; Peppelman *et al.*, 2015).

The biophysical parameters were measured at three moments in time; at the beginning of the experiment (baseline), immediately after removal of the occlusion and 30 min after removal of the occlusion. The occlusion time of 30 min corresponds to the maximum time an inside firefighting operation lasts. The skin of the under forearms was measured due to the ease of accessibility. To eliminate possible left–right effects, the type of occlusion by the jacket and cellophane was randomized. The TEWL measurements were performed in duplo and the permittivity measurements only in single fold. Every measurement was performed on a new spot on the under forearm to avoid influence of the previous measurements. The detailed test protocol is summarized in Supplementary Appendix A (available at *Annals of Work Exposures and Health* online).

The occluded environment conditions were monitored with a DHT11-sensor (D-Robotics, England), measuring the relative humidity and temperature.

The study was performed under the following laboratory conditions: room humidity 40–60% and room temperature of 20–22°C.

Participants

Participant recruitment was performed within the medical staff of the university. Participants with skin diseases e.g. psoriasis and eczema were excluded to exclude additional disturbing influences. Participants were informed about the purpose and content of the study and gave written informed consent for participation. The study was approved by the Local Ethical Committee and conformed to The Declaration of Helsinki. The panel characteristics including distribution scheme are summarized in Table 2.

Statistical analysis

The statistical analyses consisted of paired comparison of the biophysical parameters, SC thickness, epidermis thickness and their baseline measurements.

Table 2. Panel characteristics and distribution scheme.

	Age	Gender	Right	Left
IFV001	49	m	Jacket	Foil
IFV002	61	m	Jacket	Foil
IFV003	29	f	Jacket	Foil
IFV004	38	m	Foil	Jacket
IFV005	52	f	Foil	Jacket
IFV006	29	f	Jacket	Foil
IFV007	30	f	Foil	Jacket
IFV008	56	f	Jacket	Foil
IFV009	55	m	Foil	Jacket
IFV010	31	m	Jacket	Foil
IFV011	52	f	Foil	Jacket
IFV012	20	f	Jacket	Foil
IFV013	61	m	Foil	Jacket
IFV014	49	m	Foil	Jacket
IFV015	42	f	Foil	Jacket
IFV016	37	f	Foil	Jacket
AVG	43			
SD	13			

Pearson correlation analyses were performed to study the relationship between measured increased temperature and humidity within the occlusion environment and biophysical parameters TEWL, Skin Surface Water Loss (SSWL), and permittivity.

Pearson correlation analyses regarding gender and age and the baseline measurements of biophysical parameters were performed to study dependencies to identify possible risk factors. Correlations coefficients between 0 and 0.3 (0 and −0.3) indicate a weak relationship, values between 0.3 and 0.7 (−0.3 and −0.7) indicate a moderate relationship and values between 0.7 and 1 (−0.7 and −1) indicate a strong relationship. All analyses were performed with SPSS 24.0 for Windows.

Results

Correlation between the baseline biophysical parameters

No significant correlations were found between the baseline biophysical parameters (TEWL, SSWL, permittivity, and SC thickness) and the age and gender (Table 3).

Moderate correlations were found between the TEWL, age, gender, and SC thickness. Where the TEWL is proportional to age but reciprocal to the SC thickness i.e. sweating increases with age, and with a thinner SC. Regarding to gender, the baseline TEWL values of females are lower comparing to males. It also showed that there is a moderate positive correlation between SSWL and permittivity. The wetter the skin's surface, the higher the measured permittivity.

Only a weak negative correlation was found between age and the SC thickness. Indicating that volunteers with a higher age, have a lower SC thickness.

At fire scenes, firefighters are exposed to potentially harmful substances. Besides inhalation of these products, also skin contamination and the risk of dermal absorption is getting more attention. In this perspective, skin barrier impairment due to the occlusive effect of firefighter clothes could enhance the risk of penetration of hazardous substances.

The effect of a firefighter jacket and cellophane on the skin was studied in a paired comparison involving 16 volunteers. Biophysical parameters were measured before, immediately after and 30 min after ending the occlusion. RCM was used to study the skin morphology.

Immediately after wearing a firefighter jacket, TEWL values were significantly increased. This is an indication of an occlusive effect of the firefighter jacket. The skin barrier was fully restored after 30 min after occlusion with cellophane or wearing a firefighter jacket.

Differences in occlusion climate: jacket versus foil

The way of occlusion is different: the occluded environment under a cellophane foil was less increased in temperature but more increased in humidity. The results of the average temperature and humidity rise of both types of occlusion, a jacket and foil respectively, are summarized in Table 4.

Correlation between occluded climate parameters and biophysical parameters: jacket versus foil

The results of the Pearson correlation analyses of the occluded climate parameters and the biophysical parameters TEWL, SSWL, and permittivity are shown in Table 5. It showed that there was a moderate correlation between the humidity rise and permittivity measured immediately after occlusion with a cellophane foil. Indicating that the permittivity is increased when the humidity of the occluded environment is increased.

There is a negative moderate correlation between temperature rise and permittivity when measured after occlusion with a foil material. Indicating that the permittivity decreases when the temperature of the occluded environment increases.

Differences in occlusion: jacket versus foil

The results of the biophysical measurements before, immediately after and 30 min after occlusion are summarized in Table 6. It showed that all the biophysical

Table 3. Pearson correlations coefficients of the baseline values comparing the biophysical parameters.

	SC thickness	Gender	TEWL	SSWL	Permittivity
Age	−0.268	−0.421	0.302	−0.344	0.041
SC thickness		−0.023	−0.365	0.116	−0.096
Gender*			−0.312	0.098	−0.067
TEWL				−0.076	0.221
SSWL					0.454

*Male = 0, female = 1.

Table 4. Results of the temperature (Δ*T*) and humidity (ΔRVH) increase as result of the occlusion of the jacket and foil. The baseline laboratory conditions for the humidity and temperature respectively were 50 ± 10% and 21 ± 1°C.

	Δ*T* [°C]			ΔRVH [%]		
	Jacket	Foil	*P**	Jacket	Foil	*P**
AVG (SD)	10.33 (1.76)	9.07 (1.16)	0.000	12.07 (5.20)	31.27 (7.84)	0.001

*Paired-test confidence level 95%.

Table 5. Pearson correlations coefficients of TEWL, SSWL, and permittivity immediately after occlusion with a jacket and foil and increased relative humidity (ΔRVH) and increased temperature (Δ*T*) as result of the occlusion.

	TEWL		SSWL		Permittivity	
	Jacket	Foil	Jacket	Foil	Jacket	Foil
ΔRVH [%]	0.118	0.420	0.404	0.371	0.229	0.542*
Δ*T* [°C]	−0.120	−0.039	−0.420	−0.509	−0.494	−0.557*

* Correlation is significant at the 0.05 level (2-tailed).

parameters were significantly increased when occluded with a cellophane material.

Only the TEWL parameter was significantly increased when wearing a firefighter jacket. All biophysical parameters were turned normal 30 min after occlusion.

Discussion

After many studies investigating the risk of inhalation and toxicity of skin contamination for firefighters this study was the first to focus on the occlusive effect of the firefighters' clothing (Zhai and Maibach, 2001; Ogg *et al.*, 2012; Fent *et al.*, 2014; Tiedemann *et al.*, 2016; Anderson *et al.*, 2017; Harrison *et al.*, 2017). Occlusion influences the skin barrier function, in other words: the function of the skin as a 'safety shell' for the body. We showed that although the garment fabric is breathable itself, there is a substantial occlusive effect, with the average of >10% increase in humidity within the sleeve of the coat. We showed that this leads to significantly increased TEWL levels of under forearm skin, indicating that the skin barrier function is reduced when wearing a firefighter jacket.

Generally, it is assumed that placing garment fabric over the skin the occlusive effect is negligible (Agache, 2004). Fabrics however differ from each other in water vapor permeability and in absorbance of water vapor. Firefighter clothing is an advanced garment system, which provides not only protection against heat but is also waterproof. To achieve waterproofness, a thin semipermeable membrane is used which reduces the breathability of the garment significantly. From their study to evaluate the use of semipermeable membranes on experimentally induced skin irritation, Bock et al. (2009) concluded minimizing glove-induced occlusion effects are expected with semipermeable protective gloves. Apart from the fact that the experiments were not conducted with fully worn gloves, the preconditioning of the skin does not resemble a healthy skin condition which was aimed for in this study.

Besides the breathability also fitting is of importance. The fit influences the amount of air passing between the skin surface and the garment, and therefore, the amount of water carried out of the system as vaporous water, and how close the moisture is to the skin surface when the lining and/or under clothing gets wet. It must be remarked that only one size of jacket was used during the study and that fitting of the garment was not reckoned.

It is reported that the intercellular spaces in the basal layer are widened by occlusion (Golda *et al.*, 2005). In our study we did not find significant differences in skin thicknesses when applying RCM. It is likely that the time period of our acute, short-term occlusion was too short to affect the skin morphology.

When measuring the effect of occlusion there are two important aspects to consider. Firstly, an apparatus which is set upon the skin causes a type of occlusion. Especially, when performing the permittivity measurements an occlusion effect of the apparatus could be noticed. The permittivity was linearly increasing after 10 s. This characteristic is used to derive the permittivity at the start of the measurement. Secondly, the time dependency. In the protocol the measurements were performed sequentially. Ideally the measurements should be performed at the same time. Statistical analysis confirmed that the two TEWL measurements performed immediately after occlusion cannot be considered as duplo because of this dynamic effect.

The correlation study showed that the TEWL is proportional and the SC thickness is reciprocal to age. This implies that the function of the skin barrier is depending on age and decreases in time. This is in accordance with literature. It is found that the biosynthesis of the majority of SC lipids decreases significantly with age (Rogers *et al.*, 1996). Skin lipids play an important role in the permeability of the SC. Age, therefore can be considered as a risk factor. The TEWL is also moderately correlated with gender where baseline TEWL values of man were higher than those of women. In literature however there is no consensus about the relation between TEWL and gender (Machado *et al.*, 2010).

The under forearm was chosen to study the occlusive effect because of its ease of accessibility. It must be

Table 6. Results of the TEWL, SSWL, and permittivity, SC and viable epidermis + SC measurements when occluded with a firefighter jacket and a cellophane foil measured before, immediately after and 30 min after occlusion.

	TEWL $[g\ m^{-2}\ h^{-1}]$ AVG (SD)	SSWL $[g\ m^{-2}\ h^{-1}]$ AVG (SD)	Permittivity [–] AVG (SD)	SC [µm] AVG (SD)	Viable epidermis + SC [µm] AVG (SD)
Jacket					
Baseline	9.61 (2.37)	0.061 (0.029)	9.22 (4.02)	8.20 (2.92)	40.68 (4.16)
After occlusion 1st	10.56 (3.38)*	0.074 (0.060)*	10.21 (4.38)	8.95 (3.65)	42.13 (5.90)
After occlusion 2nd	10.05 (2.95)	0.054 (0.048)**			
30 min after occlusion	9.20 (2.18)	0.059 (0.023)	8.83 (3.70)		
Foil					
Baseline	9.47 (2.26)	0.062 (0.027)	8.38 (3.64)	9.51 (3.87)	43.40 (5.89)
After occlusion 1st	15.35 (3.26)*	0.101 (0.063)*	34.76 (12.48)*	8.63 (3.17)	42.20 (4.93)
After occlusion 2nd	12.31 (2.68)*,**	0.055 (0.026)*,**			
30 min after occlusion	9.18 (2.29)	0.066 (0.043)	8.85 (3.27)		

*Paired-test in reference with baseline significantly different with a confidence level of 95%.

**Paired-test in reference with 1st measurement significantly different with a confidence level of 95%.

remarked that TEWL values are strongly related to the anatomic site. TEWL values of the forehead are generally higher than of the forearm and abdomen but the palm and sole have the highest value (Machado *et al.*, 2010). Coherently, relative absorption rates using the forearm as reference showed that absorption rates of the forehead and genital area are 4.2 and 11.8 times higher, respectively (Ogg *et al.*, 2012). Therefore, the measured occlusive effect on the under forearm can be seen as a conservative estimate of the total occlusive effect of the whole firefighters' garment on the body.

The current test protocol is based on measuring the effect of occlusion on the skin barrier. TEWL measurements are generally accepted as method to evaluate the barrier function. In order to eliminate side effects by sweating the subject was positioned in a chair and room conditions were standardized. This does not reflect the physical effort of a firefighter during firefighting operations. From physiology studies of athlete's skin, sportive activity is accompanied by significant changes of skin physiology that could stress the barrier function of the skin (Luebberding *et al.*, 2013). Higher skin surface pH and hyper hydration of the SC as well as increased lipid content on the skin surface are probably caused by an increased sweat production. It is therefore expected that besides the occlusive effect of the garment, the physical effort of firefighters during firefighting operations has a superimposed effect upon the skin barrier function. This additional effect however cannot be measured with TEWL measurements.

Advice for future research

Currently the protocol is developed and tested using healthy volunteers with the aid of an acute, short-term occlusion. Important to know is how firefighters skin responds and whether the skin is affected by repetitive and long-term exposure by wearing garment daily. From studies of the effect of glove occlusion it is shown that skin barrier damage is related to the frequency and duration of exposures (Tiedemann *et al.*, 2016).

From this perspective, the hypothesis is that firefighter's skin and their response to our proposed acute short-term occlusion is different due to his chronical exposure.

It is proposed to firstly study the firefighter's skin's morphology by RCM. The hypothesis is that the morphology of firefighter's skin is different due to this repetitive long-time occlusion.

Secondly, the response of the firefighter's skin to acute occlusion is studied with the aid of the developed protocol. The hypothesis is that firefighters' skin is responding more intensely and will take longer to recover.

Conclusion

The significant increased TEWL is an indicator of skin impairment due to the occluding effect of wearing a firefighter jacket. Although this study was performed with human healthy volunteers, the developed methodology and outcome will be of value for future studies with firefighters. Continuing this research could clarify and reduce the health risks of firefighters. The preliminary results are important for manufactures and their development of innovative less occlusive clothing concepts.

Supplementary Data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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Conflict of Interest

The authors declare no conflict of interest relating to the material presented in this article. Its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

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