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INVITED REVIEW

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Measurement of transepidermal water loss, stratum corneum hydration and skin surface pH in occupational settings: A review

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Abstract

Background: The skin provides a permeable barrier which may be impaired in occupational settings. Transepidermal water loss (TEWL), stratum corneum hydration (SCH) and skin surface pH (SSpH) have been used in occupational settings to predict early onset of occupational skin diseases, to measure the effectiveness of prevention strategies for occupational skin diseases, and to assess skin condition during exposure. The aim was to compare the findings, identify shortcomings in the methodology and data reporting and furthermore, to make recommendations for future studies.

Materials and Methods: A literature study was conducted on studies published before December 2018 to provide a review on the measurement of TEWL, SCH and SSpH in occupational settings.

Results: TEWL, SCH and SSpH were previously measured in a wide variety of industries. Results between studies were highly variable, due to different study designs and different anatomical positions measured. Not all of the measurement conditions were reported and variations in study objectives led to data being reported and interpreted differently for most studies.

Conclusion: Incomplete reporting of methodology hinders comparison of bioengineering measurements. No bioengineering method has been proven useful as a predictive tool for occupational skin diseases, however, it is useful in the acute assessment of skin condition. It is recommended that future studies on TEWL, SCH and SSpH adhere to guidelines for occupational settings as far as possible to enable comparison between studies.

KEYWORDS
skin barrier function, occupational skin exposure, skin bioengineering, skin condition

1 | INTRODUCTION

The skin is the largest organ in the human body and performs many vital functions, of which the most important is forming a barrier between the internal physiological environment and the hostile external environment, where chemicals, mechanical insults, ultraviolet light or pathogenic microorganisms might be present. The skin also serves as an effective barrier to prevent the loss of electrolytes and water from the internal environment.[1] This skin barrier function is especially important in occupational settings where workers are at risk of exposure to an array of hazardous substances. In controlling exposure to hazardous exposures in the workplace, the majority of efforts have historically been directed at limiting or eliminating inhalation exposure, with skin exposure often overlooked.[2] Direct and indirect skin contact with hazardous substances is fairly common in occupational settings, and for some chemicals, the skin may be the major route of exposure.[2,3] Although the skin is a relatively effective barrier, it is more often than not impaired to some extent in occupational settings, either via mechanical or chemical insults.[2] Mechanical insult may occur through abrasion, friction or scrubbing, leading to partial or complete removal of the stratum corneum—and thus removing the skin barrier.[4] Chemical insult can occur through exposure to a combination of substances, leading to disruption of the skin barrier.[5] In cleaning and health care industries, for example, cleansing substances, solvents and detergents may alter the lipid composition of the stratum corneum and may lead to a damaged skin barrier. In other industries, exposure to weak alkalis and acids may alter the hydration of the stratum corneum, as well as have an effect on the surface pH of the skin.[4-6] Impaired barrier function may lead to increased permeation of chemicals or facilitate permeation of nanoparticles, larger protein molecules or inorganic metal compound.[2,5,7,8] Following such permeation, the skin—being a dynamic and biologically active organ—has the potential to initiate immunological effects, such as irritation, inflammation and sensitisation, as well as contribute to the development of systemic diseases and increase the risk for occupational skin diseases.[2,5,9] Besides the health effects, the impact that such exposure can have on the employee, as well as the employer, is of significant relevance. These include economic losses to both parties, due to decreased productivity, medical expenses and loss of work due to illness.[2,10] It is therefore of utmost importance that the skin integrity remains intact throughout the entirety of a work shift—and over the span of an employee's career.

The effects that occupational exposure to hazardous substances may have on the skin condition of workers may differ substantially between occupational settings. Bioengineering measurements, such as transepidermal water loss (TEWL), stratum corneum hydration (SCH), skin surface pH (SSpH) and skin temperature, have been used in various studies as an objective assessment of occupationally exposed skin. These parameters have been established as practical, sensitive and non-invasive tools that, in addition to clinical investigation, can be used to indicate—or even predict—skin damage at an early stage.[11] It has also been recommended for clinically monitoring workers who have a high risk of developing occupational dermatitis. Within this context, a large number of studies have been conducted on these parameters in controlled (clinical) environments—in order to avoid the influence of external factors. Far less research studies have been published where these parameters were measured in occupational, non-clinical settings. Within those studies, significant differences exist with regard to measurement instruments used, compensating for external influences (such as humidity and temperature), anatomical position measured and the methodology and measurement protocol used in each study.

Here we provide a critical review of studies where measurements of TEWL, SCH or SSpH were used to assess the skin in occupational settings, or following occupational skin exposure. The aim of this review is to provide a summary of these studies, along with comparisons between the relevant industries and to identify any shortcomings with regard to the measurement and reporting of results. Furthermore, we aim to provide recommendations regarding the methodology, reporting and interpretation of results for future studies.

2 | METHODOLOGY

A literature search was conducted using various databases, including Google Scholar, Scopus and EBSCO Discovery Service in order to find published studies relating to bioengineering measurement of TEWL, SCH and SSpH in occupational settings. Keywords included "skin barrier function", and/ or "transepidermal water loss", "skin hydration", "skin pH", "skin exposure" and "occupational skin exposure". Literature that was published from 1980 until December 2018 was included. Any studies that were conducted in a clinical (laboratory), controlled environment were excluded. These refer to studies where the researchers had control over the participant selection (homogenous age, ethnicity, gender) and exogenous factors (relative humidity, acclimatisation, ambient temperature, etc).

3 | TRANSEPIDERMAL WATER LOSS

In the epidermis of the skin, a water gradient exists, with the moisture content of the stratum corneum being lower than that of the deeper dermal layers.[9,12] Due to this gradient, passive diffusion of water occurs from the inner layers, towards the stratum corneum. The majority of the water evaporates from the skin surface, while a fraction of the water is retained within the stratum corneum.[12,13] This insensible loss of water from the skin, due to evaporation (in the absence of sweat), is referred to as TEWL. This diffusion gradient has a flux of 0.5-1.0 mg/cm^2/h, which can lead to a total loss of 500 mL of water from the skin per day. This is higher than the volume of water lost daily through sweat (at room temperature of up to 29°C).[9]

The water diffusion gradient is closely controlled by a fully functioning stratum corneum, and any damage that occurs to the skin as a result of chemical or mechanical insult would lead to an impairment of the skin barrier.[9] In effect, the skin loses some of its efficiency in retaining water within the stratum corneum, and due to a higher volume of water being lost through evaporation, an increase in TEWL will be detected. There is thus a direct correlation between extent of skin damage (barrier disruption) and TEWL.[12] TEWL can, therefore, be used as a very effective tool in establishing the effects of skin irritants, detergents, organic solvents, radiotherapy and skin stripping, as well as environmental influences on the skin barrier.[12]

In measuring TEWL, the density gradient of water that evaporates from the skin is indirectly measured by placing a probe perpendicularly on the measurement site. The probe is usually in the form of a closed-chamber or open-chamber method and contains two pairs of sensors (temperature and relative humidity), from which the measurement is derived.[14] Low TEWL values are indicative of an intact skin and fully functional barrier, with an increase in TEWL generally accepted as an indication of a disturbed or disrupted skin barrier.[4,14] This is in particular due to an increase in water loss through skin that has been chemically or physically damaged (an increase which correlates with the degree of impairment). However; TEWL will return to lower (normal) levels as soon as the damaged barrier has recovered.[14]

4 | STRATUM CORNEUM HYDRATION

SCH represents the water content of the uppermost layers of the skin.[4] The small amount of water that is lost through the skin (skin vapour loss) is crucial for hydration of the outer layers of the stratum corneum, as the majority of stratum corneum moisture is derived from the water diffusing from within the deeper layers of the skin.[12] The moisture is then retained within the protein-rich corneocytes that comprise the stratum corneum.[15] The presence of a natural moisturising factor (NMF) within these corneocytes increases the ability of the stratum corneum to retain water.[12] The water content of the stratum corneum can thus be considered as a delicate balance of moisture between the deep layers of the skin and the environment.[12]

Adequate moisture in the stratum corneum is important for the maintenance of several vital functions of the skin. These include maintenance of stratum corneum flexibility, maintenance of the viscoelastic skin characteristics and facilitation of enzymatic reactions involved in maturation of the stratum corneum corneocytes.[12,15,16]

SCH can be measured indirectly based on three principles. The first is based on capacitance measurement of a dielectric medium. The skin surface hydration changes the capacitance of a precision capacitor, and this is measured as a change in the dielectric constant.[17] Alternatively, SCH can be indirectly measured as the total impedance applied to the skin, or as electrical conductance.[4] Several instruments are commercially available with which SCH can be measured, and it generally consists of a probe that is applied with slight pressure on the skin. The hydration values are then expressed in arbitrary units (au).[17]

In healthy skin, the hydration of corneocytes is typically around 40 au or between 10% and 20% moisture, which is significantly lower than that of the keratinocytes in the stratum basale (stratum germinativum), the basal layer of the epidermis, as well as other cells in the body (75%-85%).[5,9] Lower SCH values represent a dry or dehydrated skin.[4] A hydration value below 10% indicates an impairment in the barrier function, causing the skin to be increasingly susceptible to further damage via irritation.[5] Insufficient skin moisture will cause a loss in skin elasticity, as well as skin flaking and cracking. This type of damaged skin will be a less effective barrier against chemicals and other irritants.[15]

5 | SKIN SURFACE PH

In chemistry, pH is generally defined as the negative logarithm (base ten) of the concentration of free hydrogen ions in an aqueous solution. It is measured on a scale of 0 (highly acidic) to 14 (highly alkaline), with a neutral point of 7. When measured in occupational settings, SSpH may provide valuable insight into the acute state of the skin in the workplace. It may also have an influence on the dissolution and partitioning of chemical substances to which workers are exposed to which in turn may influence dermal permeation of certain substances.[18,19] Some metals may undergo ionisation, leading to increased percutaneous absorption through the skin. Previously, a decrease in the pH of synthetic sweat increased the ionisation potential of metals (nickel, cobalt, chromium, gold and inorganic lead) that were dissolved in the sweat. This lead to increased permeation of these ionised metals through the skin.[7,18,20]

Although direct measurement of the skin surface pH is not possible, the extractable water-soluble compounds of the skin are measured using a glass planar electrode connected to a voltage meter.[10] These water-soluble compounds are collectively made up of the components of the stratum corneum and the sebaceous and sweat gland secretions and contribute to the acidic milieu of the skin surface.[21]

In general, the pH of the skin surface is quite acidic and in the range of 4.6 to 5.6.[9] The acidity of the skin provides an optimal environment for ceramide and lipid functioning, as well as normal functioning of enzymes. Furthermore, it is important for maintenance of the integrity and cohesion of the stratum corneum and homeostatic regulation of the skin barrier function.[9,10,22] Acidic SSpH (below 5.0) is more beneficial for the general condition of the skin, when compared to skin with a pH above 5.0, as indicated by measurements of barrier function, moisturisation and scaling.[22] Furthermore, repair of damaged skin will occur normally at an acidic pH (5.0 or lower), but may be delayed at a neutral or alkaline pH (>7).[16,22]

6 | SKIN PARAMETER MEASUREMENT—SKIN RELATED AND OTHER ASPECTS

Measurements of TEWL, SCH and SSpH are affected by various endogenous, as well as exogenous factors, which have been discussed in detail elsewhere.[4,10,14,17,19,23,24] Endogenous factors include the age, gender and ethnicity of the participants, anatomical positions on which measurements are taken, state of the skin (moisture, sweat, sebum, disease state), as well as genetic predisposition.[4,5,10,21] Exogenous factors include ambient temperature, relative humidity, time of day, skin contamination, application of cleanser, creams or detergents, topical application of cosmetic products, occlusion and even topical antibiotics. All of these factors may lead to discrepancies in the data collected and provide a major challenge for the interpretation of data—as well as comparison with other studies. In clinical settings, these effects, as well as some endogenous factors, may be minimised and measurements of TEWL, SCH and SSpH may be easily performed under well-regulated conditions. In non-clinical (occupational) settings, however, the conditions under which measurements are performed may be difficult to control.

TEWL, SCH and SSpH have been measured on a wide variety of anatomical positions in occupational settings (refer to Figure 1). TEWL measurements have been made on the dorsum (back)

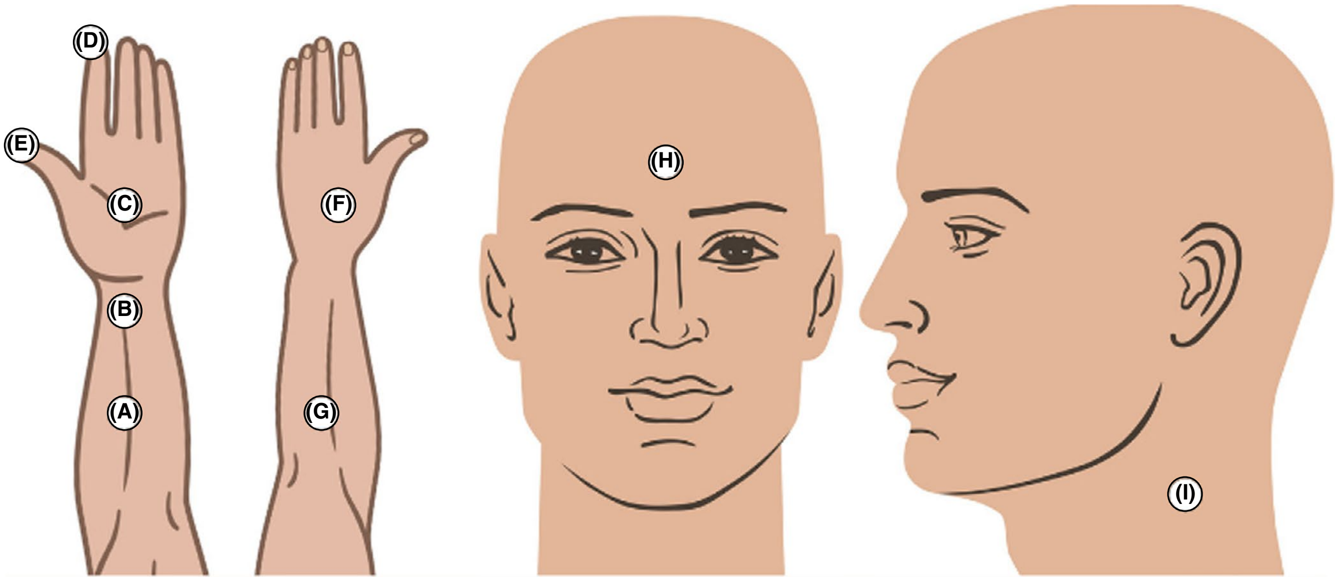

FIGURE 1 Schematic representation of the anatomical positions on which skin bioengineering measurements are taken in occupational settings: (a) volar forearm, (b) wrist, (c) palm, (d) thumb, (e) index finger, (f) back of hand, (g) extensor forearm, (h) forehead and (i) neck (Dreamstime, 2018)

of hand,[3,4,6,13,25-29] volar forearm,[11,25,27,29-32] extensor forearm,[25] index finger,[6] thumb,[6] palm,[4,6,27] wrist,[4,28] neck[6] and forehead.[4,6]

SCH was measured on the volar forearm,[3,11,27,29,32] palm,[4,27] dorsum of hand,[3,4,27-29] forehead[4] and wrist.[4,28]

SSpH was measured on somewhat fewer anatomical positions, including the volar forearm,[3,11,27] wrist,[4] palm,[4,27] dorsum of hand[3,4,27] and forehead.[4] Results compared between these anatomical positions are highly variable, which, along with the manner in which results from these positions are reported, makes comparison of results for anatomical positions between studies practically impossible.

Very useful guidelines have been recommended for the measurement of TEWL, SCH and SSpH in clinical settings.[14,17,23] These guidelines have been adapted for measurement in occupational settings in an effort to make studies in occupational settings more reliable and comparable.[4,10,19,24] At the same time, the researchers acknowledged the difficulty of adhering to these guidelines in occupational settings. These include an acclimatisation period of 20 minutes in a temperature- and humidity-controlled environment prior to measurements and refraining from skin washing (with water or detergent products). In occupational settings, the researcher is dependent on the available work force and has very little control over selecting participants of the same age, gender and ethnicity. Therefore, these types of recommendations are challenging to follow in occupational settings. Some endogenous and exogenous factors can, however, be controlled and homogenised throughout different studies to some extent. These include the anatomical positions on which measurements are made, excluding damaged and diseased skin, eliminating instrumentation variation by using standardised equipment and following calibration procedures.[4,10,19,24] In occupational settings, it is extremely difficult to control some exogenous factors, especially ambient temperature and relative humidity and can therefore not always be as closely controlled as is recommended for clinical settings. These factors should be reported when taking these measurements. What is of utmost importance is a clear indication of recommendations (guidelines) that could not be adhered to, with an accompanying reason as to why adherence was not feasible during the measurements. Many of the studies that were reviewed failed to either describe the experimental conditions to a full extent, failed to adhere to guidelines that have previously been suggested (even those guidelines recommended for clinical studies) and/or failed to report reasons for not following such guidelines. Therefore, although an attempt is made in this study to review, interpret and compare different skin bioengineering studies in occupational settings, this could only be achieved to some extent due to significant experimental differences, including—but not limited to—the variation in types of industries investigated and the different types of instruments used (including, but not limited to different evaporimeters, tewameters, derma units, skin monitoring centres, corneometers and pH meters). Typical occupations that were of particular interest in these studies included metal industries, nursing, hairdressing, food industries, cement industries, printing and paperwork.

Table 1 provides a summary of various methodologies used in the relevant published research that is available on measurement of TEWL, SCH and SSpH in occupational settings. Some of these studies will be discussed in detail, while others are only summarised, due to a lack of information provided.

7 | TRANSEPIDERMAL WATER LOSS IN OCCUPATIONAL SETTINGS

TEWL has been measured in a limited number of occupational settings. These include the metal industry, hairdressing, nursing, rayon manufacturing, cement industry, food industry, printing and paperwork.

7.1 | Metal industry

The measurement of water loss in occupational settings dates as far back as 1986, when skin vapour loss (SVL) was measured on the skin of metal industry workers exposed to mineral oil and water-soluble oil.[25] SVL is a measurement of the water loss from the skin, which includes TEWL, as well as a small quantity of water vapour from the sweat glands. They reported that the mean SVL value on the volar and extensor sides of the forearms of workers exposed to mineral oil were significantly higher ($P \leq 0.05$) than that of the unexposed group. The workers that were exposed to water-soluble oil showed slightly, but not significantly, higher mean SVL values than the unexposed group. They concluded that the increase in SVL that occurred throughout the study was attributed to exposure to oils, which either caused toxic damage to the skin or altered the skin hydration status. Furthermore, a conclusion was made that SVL measurements could be used to detect an effect of chemical exposure, such as oil on clinically normal skin and could thus be used for monitoring exposed workers that are at risk of occupational contact dermatitis (OCD). Following this study, and using a similar hypothesis, the point of prevalence of cutting fluid dermatitis and TEWL changes of machinists were compared.[33] They conducted a prospective study to assess the effectiveness of a barrier cream and an after-work emollient cream as preventative measures for cutting fluid dermatitis. The researchers acknowledged that their study population was too small for any statistically significant findings. Nevertheless, the study was performed under fairly standardised conditions, and during the first six weeks, the differences in mean TEWL values increased rapidly, after which it remained fairly consistent throughout the remainder of the study. Incidences of cutting fluid dermatitis were lower in the group that used the after-work moisturisers, when compared to the group that used barrier creams, as well as the control group. A fivefold increase occurred in mean TEWL values between workers with cutting fluid dermatitis and those with no signs of dermatitis within the first three weeks of exposure. They suggested that this could be used to identify individuals who may be susceptible to cutting fluid dermatitis. Despite this, no correlation was found between TEWL and the risk for OCD and TEWL could not be confirmed as predictor for OCD, as was found previously.[25]

In a following study, TEWL changes in machinists exposed to mineral oils were compared with that of unexposed paramedics.[34] An initial increase was observed in the TEWL of the machinists, but reached a plato after three weeks of study, while the mean TEWL values of the control group remained fairly constant for the duration of the study. In another study, the validity of skin bioengineering methods (including skin hydration and TEWL) as predictive measurements for the development of hand eczema was investigated in metal-worker trainees.[35] No single bioengineering method could be used as a suitable screening test, but the researchers concluded that bioengineering measurements in combination with various irritation tests would allow high-risk individuals to be identified.

TEWL was measured in metal workers and a slightly but significantly lower TEWL was reported in a group of workers using barrier cream after a one-year follow-up, indicating a protective effect.[36] No other significant difference in TEWL was reported for other subgroups. The researchers concluded that complete dermatological examinations at the workplace cannot be replaced by bioengineering techniques (such as TEWL). They described the supplementary benefit of skin bioengineering measurements to be apparently low, possibly due to difficulties in achieving standardised measurement conditions and other technical reasons.

TEWL was measured on various anatomical positions of workers employed at a base metal refinery.[6] They observed impaired barrier function, as indicated by elevated TEWL values, even before the work shift commenced. In a later study, bioengineering parameters, including TEWL, were measured as a way of assessing changes in skin barrier function in base metal refinery workers, exposed to acidic chemicals and base metals.[4] TEWL values increased significantly from the onset to the end of the work shift. In both studies, the barrier function is impaired, which could lead to increased permeation of sensitising metals, such as nickel and cobalt. These changes in skin barrier function, as indicated by significant changes in TEWL, were attributed to the exposure of these workers to sulphuric acid.

7.2 | Hairdressers and nurses

TEWL was measured in apprentice hairdressers and nurses and found that hairdressers had an increased risk of hand dermatitis at TEWL <15 $g/m^2/h$ of the hand, but the increased risk was not statistically significant.[30] No relationship was observed for nurses. The lack of relationship with TEWL as a continuous variable indicates that there was no linear increase in the risk of hand dermatitis with increasing TEWL on the hand or forearm. The findings of this study do not support the hypothesis that an elevated level of TEWL increases the risk of hand dermatitis. Skin bioengineering measurements were investigated (TEWL, microcirculation, capacitance, pH, sebum and temperature) of hairdresser apprentices.[27] None of the bioengineering parameters—not even a combination thereof—could be used to indicate an elevated risk for developing dermatitis. There was, however, a significant increase in TEWL within the first year of training. TEWL was compared on the hands of nurses with an administrative control group.[28] The TEWL of the nurses were significantly higher than that of the control group on all anatomical positions. The higher TEWL, along with clinically relevant signs of irritant contact dermatitis, indicated skin barrier damage among operating room nurses, possibly due to exposure to water and detergents, while no such observation was found in the control group.

The incidence of hand dermatitis, the impact of potential risk factors and the efficiency of skin bioengineering techniques (TEWL and SCH) were evaluated in a prospectively followed cohort of apprentice nurses.[29] The authors concluded that a higher baseline TEWL is not necessarily a good indicator for increased risk of hand dermatitis. They observed a significant difference between initial TEWL examination and intermediate measurement on the dorsal hand, but not between intermediate follow-up and final examination. On the forearm, no statistically significant changes in TEWL occurred. No statistically significant differences were found between the initial, intermediate and final SCH measurements. The authors concluded that even though elevated TEWL has previously been linked with an increased risk of hand dermatitis, this parameter (or any other skin parameters) cannot be used as a predictor of occupational hand dermatitis.

The skin condition of student auxiliary nurses was examined in order to determine the effectiveness of an educational programme in preventing work-related skin problems.[13] Three measurements of TEWL were made on the back of the dominant hand with an evaporimeter (Servomed, Stockholm, Sweden) and the mean value used in statistical analyses. They found a statistically significant increase in TEWL in the control group, who did not participate in the educational programme ($P < 0.005$), after ten weeks of training, but not in the intervention group, who participated in the prevention programme. The subclinical changes observed in the skin and evaluated by TEWL indicated that the programme had a significant positive effect on behaviour.

7.3 | Manufacturing

TEWL was measured in rayon manufacturing workers exposed predominantly to carbon disulphide and sulphuric acid.[31] Significant differences in baseline TEWL values were reported between exposed Chinese workers and a control group. The researchers suggested that baseline TEWL values are useful in evaluating the changes that occur in skin barrier function, following repeated occupational exposure to chemical insults.

7.4 | Cement workers

TEWL was measured in cement workers exposed to high levels of chromium, as an indicator for the assessment of skin barrier function.[38] The TEWL of workers that were exposed to high levels of chromium was significantly higher than those exposed to lower chromium levels (as indicated by urinary chromium concentration and its positive correlation with TEWL). These results indicated that chromium exposure led to skin barrier disruption, and this effect was dose-dependent. This was attributed to the direct skin contact with chromium, as well as the reactive oxidative stress (ROS) induced during chromium metabolism.

In a similar study, TEWL was used to investigate the skin barrier function of cement workers, following exposure to chromium. Urinary chromium concentration was used to determine chromium exposure level.[39] TEWL was significantly higher in workers with high levels of chromium than those with low chromium levels. The conclusion was made that the barrier function of the workers may be disrupted by chromium. Furthermore, impairment of the skin barrier function may lead to increased permeation of chemicals that are present in the working environment, following direct contact with the skin.

7.5 | Food industry

In the food industry, occupational skin diseases, such as irritant contact dermatitis and hand eczema, may manifest due to contact with water, organic compounds from ingredients and detergents.[38] Therefore, the continuous use of personal protective equipment, such as gloves and protective moisturisers, is highly recommended for the prevention of occupational contact dermatitis. The effectiveness of different prevention strategies (training in skin protection and care, as well as prevocational skin hardening with UV light) in prevention of hand dermatitis of food industry workers was investigated.[40] Statistically significant differences were found in TEWL baseline values between an intervention and control group, which was an indication of the effectiveness of skin protection and skin care in maintaining optimal skin condition in food industry trainees.

7.6 | Printing and paperwork

In the printing industry, the skin of workers is constantly exposed to washing and cleaning agents for printing machines, as well as paint and other irritants. However, mechanical skin damage may also occur in these industries. Various risk factors can be found in printing industries, such as low ambient humidity, handling of paper and exposure to dust, causing mechanical irritation of the skin to be the dominant type of exposure in printing.[3]

The skin of printing workers has been clinically examined using TEWL, SCH and SSpH measurements. A positive trend between erythema on the forearms and TEWL was found; however, a significant positive correlation between these factors could not be established. They concluded that TEWL is not useful in indicating skin scaliness, as the results did not indicate a strong and uniform relationship with skin lesions.[3]

In a following study, the skin condition of workers in two newspaper printing plants was investigated.[11] The predominant exposures included paper dust. The researchers found no statistically significant correlation of TEWL with erythema or scaliness on exposed skin. They found higher median TEWL values on the exposed hands of workers, than on the forearms, which was typically protected by clothing. They concluded that due to skin irritation, TEWL may increase to some extent.

7.7 | Other industries

A field study was conducted among workers in the fish processing industry to obtain information about skin surface temperature, TEWL and electrical capacitance and the interaction between each parameter during work.[39] Their study population included a wide variety of different occupations, each with different exposures. These included fish processing workers, cleaners, metal workers, gut cleansers, nurses and office workers, each with different exposures. Fish workers were exposed to fish products and cold temperatures (iced fish and water); cleaners were exposed to soap, detergents and water; metal workers were exposed to cutting oils, lubricants

TABLE 1 Summary of skin bioengineering measurement methodology in occupational settings

Industry	Exposure	N	Age (years)	Gender	Acclimatisation (min)	RH (%)	Temperature (°C)	Number of Measurements	Reference
Transepidermal Water Loss									
Metal Industry	Oils	205	NR	M	NR	59	21	NR	35
	Oils	54	25-28	M, F	10	55	21-22	NR	25
	Oils	33	22	M, F	10-15	44-54	25-27	2	33
	Oils	51	20-23	M, F	10-15	NR	NR	2	34
	Cutting fluids	1020	18-62	M	NR	61.2	17.7-27.7	3	36
	Base metals	26	NR	NR	NR	NR	NR	At least 2	6
	Base metals	12	NR	M	NR	40-43	21-23	NR	4
Hairdressing & Nursing	Wet work	33	23-50	F	15-20	45-55	19-21	NR	28
	Wet work	107	NR	NR	30-45	NR	NR	3	13
	Wet work	14	17-41	M, F	NR	NR	NR	NR	29
	Wet work	111	17-23	M, F	NR	27-62	16-24	2	3
	Wet work	91	NR	M. F	15	40-45	20-21	3	27
Manufacturing	Chemicals	16	26-52	M	30	53.4 ± 11.6	26.6 ± 1.1	NR	31
Cement	Chromium	45	46.9	M, F	NR	NR	NR	NR	36
	Chromium	108	26-65	M, F	30	53.4 ± 11.7	26.6 ± 1.2	NR	37
Food Industry	Wet work	63	17.7 ± 1.34	M, F	NR	NR	NR	NR	38
	Various	143	Various	M, F	0	Various	Various	10	39
Printing	Wet work	28	23-61	M		60	23.4 ± 24,5	NR	3
	Wet work	71	27-61	M, F		NR	20.2 ± 22.6	NR	11
Other	Ultra-low humidity	61	25.4±0.6	M, F	30	60	25	Continuous	31
Stratum Corneum Hydration									
Metal Industry	Oils	54	25-28	M	10	55	21-22	Continuous	34
	Base metals	12	NR	M	NR	40-43	21-23	NR	4
Hairdressing	Wet work	33	23-50	F	15-20	45-55	19-21	NR	27
	Wet work	32	16-55	M, F	10	NR	NR	3	15
Nursing	Wet work	14	17-41	M, F	NR	NR	NR	NR	28
Cement	Chromium	45	46.9	M, F	NR	NR	NR	NR	36
Food Industry	Various	143	Various	M, F	0	Various	Various	10	39
	Various	20	16-55	M, F	10	NR	NR	3	15
Nursery	Wet work	42	16-55	M, F	10	NR	NR	3	15
Office & Print	Wet work	28	23-61	M		60	23.4 ± 24.5	NR	3
	Wet work	38	16-55	M, F	10	NR	NR	3	15
	Wet work	71	27-61	M, F		NR	20.2 ± 22.6	NR	11
Other	Ultra-low humidity	61	25.4±0.6	M, F	30	60	25	Continuous	31
Skin Surface pH									
Metal Industry	Base metals	12	NR	M	NR	40-43	21-23	NR	4
Hairdressing & Nursing	Wet work	91	NR	M. F	15	40-45	20-21	3	26
Printing	Wet work	28	23-61	M		60	23.4 ± 24,5	NR	3
	Wet work	71	27-61	M, F		NR	20.2 ± 22.6	NR	11

The average ambient air temperature and relative humidity at the measurement sites in fish processing industry was 20°C and 50%; in hospitals 23°C and 34%; in metal industry 23°C and 26% and in slaughterhouse 22°C and 48%.

and detergents; gut cleaners were exposed to intestine products, concentrated saline solution and water; nurses were exposed to wet work; and office workers were exposed to dry air and paperwork.

During work, the workers in the fish processing industry had very low skin temperature and very low TEWL on the fingers and palms when compared to the control subjects, with a significant positive correlation between skin temperature and TEWL on all areas. After- work, however, the TEWL increased quite rapidly to a higher value (higher than baseline, even). They concluded that although the workers had low TEWL values (which usually indicated intact barrier), an impaired barrier could in fact be masked by the low skin temperature during work.

Low temperature and low relative humidity have been associated with irritant hand dermatitis.[11] Changes in barrier function were assessed in workers who were occupationally exposed to ultra-low humidity and to evaluate whether the duration of exposure indicated a dose-response relationship with TEWL.[32] These workers were recruited from assembly lines in an enclosed facility, where the humidity was maintained at 1.5 ± 0.4%. TEWL decreased significantly within two weeks of exposure to ultra-low humidity. The TEWL of the exposure group was significantly lower than that of the control group. Following chronic exposure to ULH, TEWL slowly increased, although this increase was slow and incomplete. The gradual increase of TEWL over the course of the study could indicate that the barrier function of the skin may return to normal values through natural adaptation during extended exposure to an ultra-low humidity environment.[32]

8 | STRATUM CORNEUM HYDRATION IN OCCUPATIONAL SETTINGS

In some occupational studies, SCH has been measured to determine the skin condition of workers, often in conjunction with other bioengineering techniques, such as TEWL or SSpH. Occupational settings where these measurements were done are limited to the metal industry, hairdressing and nursing, printing, paperwork and office work.

8.1 | Metal industry

The validity of SCH as a predictor for the development of hand eczema in metal-worker trainees was investigated, but no positive results could be found to indicate that SCH could be used as a validated screening test.[35] They could, however, conclude that a combination of various irritation tests is effective in identifying individuals at high risk of developing hand eczema.

The SCH of base metal refining (BMR) workers was previously investigated.[4,6] In both studies, SCH measurements indicated slightly dry skin on the hands of workers. In 2010, SCH measurements indicated slightly dry skin on the hands at the start and end of the work shift. In 2013, variable SCH values were obtained, with a significant decrease in SCH during the work shift, although it recovered to baseline values at the end of the shift. In both studies, the barrier function was impaired, as indicated by significant changes in TEWL and SCH, due to skin exposure to acidic chemicals.

8.2 | Hairdressers

Occupations such as hairdressing are known to have high risks of occupational contact dermatitis, usually manifested as irritant contact dermatitis. The skin hydration levels of hairdressers were investigated in order to determine whether they had a lower than normal skin moisture content.[15] They found the skin of hairdressers to be abnormally dry and attributed this to frequent contact with chemicals (hair products and cleansers) at work, as well as water.

8.3 | Nurseries

The skin moisture levels of pre-school nursery caretakers were investigated.[15] The caretakers tended to have abnormally dry skin, due to direct contact with substances such as cleanser, lotions and water. The skin dryness did not correlate with the reported incidence of skin problems.

8.4 | Nursing

The TEWL and SCH on the hands of nurses were compared with an administrative control group.[28] The TEWL of the nurses were significantly higher than that of the control group on all anatomical positions, while SCH was significantly lower on all anatomical positions, except the dominant wrist.

The incidence of hand dermatitis and the efficiency of skin bioengineering techniques, such as SCH, in predicting the risk of dermatitis in apprentice nurses was evaluated.[29] The aim was to evaluate the incidence of hand dermatitis, the impact of risk factors and the efficiency of skin bioengineering methods in a prospectively followed cohort of apprentice nurses over a period of three years. They found no statistically significant differences between initial (baseline), intermediate (after one year) and final (after three years) SCH measurements and concluded that it cannot be used as a predictor of occupational hand dermatitis.

8.5 | Printing, paperwork and office work

Korinth et al. investigated the skin moisture content of printing workers and reported a significant positive correlation with erythema and skin capacitance.[3] They concluded that skin capacitance could be used as a sensitive tool to indicate skin hydration status and to predict skin scaliness. Furthermore, they found the capacitance of scaly skin to be higher than that of skin without scales. In a following study, a negative relationship was found between skin capacitance and skin scaliness on the hands.[11] This was indicated by a lower SCH (dryer skin) in workers with scaling, when compared to workers without scaling. In all the groups investigated, the capacitance values were lower on the hands (exposed skin) than on the forearms (protected by clothing). They concluded that skin capacitance is a useful tool in observing early onset skin changes in workers with predominantly physical irritation.

The skin moisture content of office workers was investigated.[15] The aim of the study was to determine whether workers in modern, air-conditioned offices, resulting in low humidity, might show similar skin effects to those employed in hairdressing or catering industries, that is development of dry skin. They found the skin of the office workers to be abnormally dry but could not conclude whether the dry skin was due to air conditioning, especially as many other factors (environmental conditions, such as low ambient humidity and frequent hand washing) can cause skin damage, resulting in abnormally dry skin.

8.6 | Other industries

It was found that the skin hydration of workers employed in ultra-low humidity decreased within two weeks of exposure.[32] However, no statistically significant differences were observed between SCH of exposed versus unexposed groups.

8.7 | Food and catering industry

Previously, it was found that 50% of catering workers had extremely dry or very dry skin and the level of dryness correlated with the level of exposure to substances that can reduce skin moisture (sugar, flour and wet work).[15]

The workers in a fish processing industry had high skin hydration, measured as capacitance during work.[42]

9 | SKIN SURFACE PH IN OCCUPATIONAL SETTINGS

The measurement of SSpH in occupational settings is extremely limited with studies only found for the metal industry and printing and paperwork.

9.1 | Metal industry

A decrease was found in SSpH values measured on the skin of BMR workers during the work shift.[4] This decrease in SSpH was attributed to exposure to acidic elements in the working environment.

9.2 | Printing and paperwork

The SSpH of workers employed in printing plants was investigated.[3,11] In the first study, they found the skin surface pH to be in the acidic range on the hands and forearms of all printing workers. A positive correlation between SSpH and systemic exposure to wet work, investigated via biological monitoring, could not be established.[3] In their second study, they found a significant correlation of SSpH on the hands and scaling of the hands.[11] They concluded that SSpH seems to be associated with skin damage, as the SSpH on healthy skin is lower than that on damaged skin. It is thus a suitable assessment tool for occupational skin exposure studies.

10 | IMPLICATIONS OF SKIN PARAMETER MEASUREMENT IN OCCUPATIONAL SETTINGS

The majority of studies that investigated measurements of TEWL, SCH and SSpH aimed at finding a (predictive) correlation between parameter measurement and the onset of occupational skin diseases, such as contact dermatitis.[25,29,30,33-35] Only one study succeeded in proving this, but was later criticised for a weak experimental design.[25] Other studies used skin bioengineering measurements as tools of assessing the effectiveness of various interventions in preventing skin diseases.[13,36] Although all of these studies provide quite valuable information with regard to TEWL, SCH and SSpH in various occupational industries, the manner in which the data are interpreted makes it challenging to compare with other studies, who aimed at investigating the change that occurred in the skin barrier over the work shift, instead of investigating the predictive values of these parameters.[4,6,28,32]

No single bioengineering measurement has thus far been found to be used as a valid screening test for occupational skin diseases. A combination of short irritation tests, along with measurement of SCH, could contribute towards identifying workers that may have a high sensitivity and thus a high risk for occupational skin diseases—hand dermatitis in particular—although with quite low specificity.[35] Very little evidence is available to support the hypothesis that skin bioengineering methods can be used as indicators for the development of occupational skin diseases. However, all evidence points towards these parameters being effective indicators of the acute condition of the skin following occupational exposure. These parameters, and SSpH in particular, may influence the consequential effects following such exposure, as has been demonstrated by increased permeation following a decrease in SSpH of synthetic sweat.[4,6,10,20] Furthermore, the remarkable healing properties of the skin and continued renewal of skin layers through desquamation of corneocytes make it extremely difficult to predict (using only bioengineering measurements) the state of the skin in the long term and thus whether skin conditions, such as hand eczema and irritant contact dermatitis, might occur in the future. Studies that aimed at using bioengineering methods to measure acute changes in skin barrier function showed much more conclusive results than those aimed at using these methods as occupational skin disease predictors.[6,31,32] Despite the apparent success of these studies, and the obvious contribution that it could make towards promoting a safer and healthier workplace, still a very limited number of studies have been published that measure and report actual measurements of skin condition after exposure. Although measurement of TEWL, SCH and SSpH have a wide variety of applications, especially in clinical settings, perhaps in occupational settings it should in future studies be utilised to investigate the acute state (changes) of the skin barrier, instead of attempting to make long-term predictions regarding the skin.

It is extremely difficult to achieve the recommended clinical measurement conditions for TEWL, SCH and SSpH in occupational settings, which further contributes to the challenges that arise during the interpretation of data and the comparison with other studies. A large degree of variation exists in the ambient conditions (temperature and relative humidity), as well as anatomical positions on which skin bioengineering parameters were measured. In some of these studies, a significant lack of information exists regarding the exact methodology of measurements, including acclimatisation time (if any), types of instruments used and the calibration of instruments and number of measurements on each anatomical position. Without a detailed explanation of the methodology used, it is up to the reader to conclude as to why such information was not reported. In order to achieve trustworthy results on TEWL, SCH and SSpH in occupational settings, researchers should make an attempt at strictly adhering to the guidelines and recommendations that have been provided.[4,10] Although several researchers have declared their adherence to the guidelines in literature, the fact is that some methodology still deviates from these guidelines to a great extent. Measurements conducted in the workplace are usually made before, during or after the work shift. This can provide numerous challenges to the researcher, the employee (participant) and employer. Measurements taken before or after the work shift could implicate that a worker should arrive at work earlier or stay later than usual, without receiving compensation, while measurements during work shift could lead to interruption of work and loss of productivity.[19] All of these factors should be acknowledged by the researcher, and if adherence to guidelines was not possible, accompanying reasons should be made available.

11 | LIMITATIONS FOR OCCUPATIONAL STUDIES

Several limitations exist for the measurement of skin bioengineering parameters in occupational settings, some of which have already been addressed in the preceding sections. The major obstacle encountered in such studies is the (in)ability to strictly adhere to all recommendations for standardisation. Acclimatisation of workers before measurements is a time-consuming procedure and interferes with work flow. The properties of the skin are difficult to optimise under working conditions. Restricted hand washing and omitting topical application over a period of 24 hours prior to measurements seem hard to achieve at workplaces with immense skin contamination. It is therefore suggested that future studies should aim at further clarification of the role of TEWL, SCH and SSpH in occupational settings. Despite the obstacles that some occupational studies may present, these types of studies are needed to acquire information related to the skin condition in working environments.

12 | CONCLUSION

Incomplete reporting of methodology used to measure TEWL, SCH and SSpH makes comparison between occupational studies extremely challenging. Adherence to measurement guidelines for clinical settings has been adapted and published for occupational settings and should be adhered to as far as possible in order to ensure better interpretation and comparison of results. Deviations from the guidelines should be reported, with accompanying reasons why standard measurement protocol could not be followed. With the use of TEWL, SCH and SSpH to predict occupational skin diseases proving to be unsuccessful, more recent studies have focused on using these measurements to assess the effectiveness of skin intervention programmes or to acutely assess the skin condition during exposure—and some have done so quite successfully.

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