Chromium released from leather – I: exposure conditions that govern the release of chromium(III) and chromium(VI)

Yolanda S. Hedberg[1,2], Carola Lidén[1] and Inger Odnevall Wallinder[2]

[1] *Unit of Occupational and Environmental Dermatology, Institute of Environmental Medicine, Karolinska Institutet, Nobels väg 13, Box 210, SE-17177, Stockholm, Sweden and* [2] *Division of Surface and Corrosion Science, Department of Chemistry, School of Chemical Science and Engineering, KTH Royal Institute of Technology, Drottning Kristinas väg 51, SE-10044, Stockholm, Sweden*

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Summary

Background. Approximately 1–3% of the adult population in Europe is allergic to chromium (Cr). A new restriction in REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) based on the ISO 17075 standard has recently been adopted in the EU to limit Cr(VI) in consumer and occupational leather products.

Objectives. The aim of this study was to critically assess key experimental parameters in this standard on the release of Cr(III) and Cr(VI) and their relevance for skin exposure.

Material and methods. Four differently tanned, unfinished, leather samples were systematically investigated for their release of Cr(III) and Cr(VI) in relation to surface area, key exposure parameters, temperature, ultraviolet irradiation, and time.

Results. Although the total release of Cr was largely unaffected by all investigated parameters, except exposure duration and temperature, the Cr oxidation state was highly dynamic, with reduced amounts of released Cr(VI) with time, owing to the simultaneous release of reducing agents from the leather. Significantly more Cr(III) than Cr(VI) was released from the Cr-tanned leather for all conditions tested, and it continued to be released in artificial sweat up to at least 1 week of exposure.

Conclusions. Several parameters were identified that influenced the outcome of the ISO 17075 test.

Key words: allergic contact dermatitis; chromium(III); chromium(VI); ISO 17075; leather; metals; occupational; restriction.

The amount of chromium (Cr) released from leather, and its oxidation state (trivalent or hexavalent) and speciation (chemical form, e.g. Cr(III) oxalate), are key parameters for both ecotoxicological and human health considerations (1–5). Contact allergy to Cr is the third most common metal allergy, after allergy to nickel and cobalt, affecting approximately 1–3% of the adult general population (6). It is a severe allergy with a poor prognosis (7, 8). Cr(VI) in cement has been an important cause of Cr allergy in construction workers. Prevention of Cr allergy among construction workers by limiting Cr(VI) in cement has been shown to be successful in Nordic countries and Germany (9, 10). Cr compounds may be present in cosmetic products. Annex IV of the Cosmetic Products Regulation (11) lists Cr-containing colorants allowed in cosmetic products under certain conditions, such as that they are rinse-off products or free from Cr ions [Cr(VI)]. Annex II lists substances that

Correspondence: Yolanda S. Hedberg, Division of Surface and Corrosion Science, Department of Chemistry, School of Chemical Science and Engineering, KTH Royal Institute of Technology, Drottning Kristinas väg 51, SE-10044 Stockholm, Sweden. Tel: +46 8 790 6878; Fax: +46 8 208284. E-mail yolanda@kth.se

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are prohibited in cosmetic products, including several Cr compounds. Published recommendations on the Cr content in detergents and cosmetics suggest that the level should normally not exceed 1 ppm (12, 13). Leather products have, since the 1990s, attracted increasing attention as a cause of Cr allergy and dermatitis (14, 15). More than 90% of the leather produced worldwide (~ 2 billion m^2) is Cr-tanned (16–18). Between 7% and 50% of ~ 9500 leather products tested and reported since the year 2000 contain Cr(VI) at concentrations above the limit of detection (3 $mg/kg_{leather}$) of the ISO 17075 standard (19–23). A limitation of Cr(VI) in leather was initially proposed by Denmark (24), and it is anticipated that a restriction will enter into force within the EU in 2015 (25). It is based on the ISO 17075 standard (26) for leather products, which stipulates Cr(VI) determination in leather by extraction of leather powder in de-aerated phosphate buffer for 3 hr. The scientific literature, the ISO standard and the restriction all focus on the release of Cr(VI) from leather, without considering the release of Cr(III). The main arguments are that Cr(III) is assumed to be retained within the leather, whereas Cr(VI) is soluble (27, 28), that chromate [Cr(VI)] is considered to be a more potent allergen, and that Cr(VI) compounds are able to induce allergy and dermatitis at lower exposure levels than most Cr(III) compounds (6, 27, 29, 30).

Cr contact dermatitis requires a Cr(III)–protein conjugate to be formed in the skin (5, 31). Cross-reactivity between Cr(III) and Cr(VI) in Cr-allergic individuals has been suggested (5, 32), as chromate can be reduced to Cr(III) in the skin. This means that a person who is Cr-allergic may react to both Cr(III) and Cr(VI). However, this depends on many factors (condition of the skin, skin diffusion properties of the compound, concentration, and sensitizing species). It has been observed in several studies that different Cr(III) and Cr(VI) compounds have different skin diffusion properties, skin solubility, and sensitizing potential, characteristics that depend on many factors such as charge, size, and speciation (4, 33–35).

The aim of this study was to quantify the release of Cr(III) and Cr(VI) from differently tanned, unfinished leather samples, and to investigate the influence of stipulated test conditions of the ISO 17075 standard, and other key exposure parameters, such as temperature, duration, surface area, and solution de-aeration.

Material and Methods

Leather

Four differently tanned, unfinished leather samples (all from cattle) from normal production were received from three European tanneries. All materials were tanned and post-tanned, but not coated and finished (so-called crust leather). Detailed descriptions of general leather processing steps, always including the tanning and post-tanning steps, are given in (16, 18). The leather and tanning procedures are described below:

1 $Cr^{Cr}{}_{gloves}$: Cr-tanned (post-tanning: Cr), intended for use in working gloves (generally low-price leather);
2 Cr^{Cr}: Cr-tanned (post-tanning: Cr and synthetic tannins);
3 Cr^{veg}: Cr-tanned (post-tanning: vegetable and synthetic tannins);
4 Veg^{veg}: vegetable-tanned (post-tanning; vegetable tanning by mimosa).

The Cr^{Cr} and Cr^{veg} leather samples were selected to investigate the effect of post-tanning. These samples had been identically treated and Cr-tanned, but with different post-tanning processes, by the same tannery. The Veg^{veg} leather was investigated for comparative reasons.

Exposure conditions

The leather samples were exposed (extracted) at the different experimental settings described in Table 1. Ultrapure water (18.2 MΩ/cm) was used as the solvent for all solutions, and all equipment was acid-cleaned (10% HNO_3 for at least 24 hr) and then subjected to four subsequent rinsing events with ultrapure water prior to use. Triplicate samples of each leather sample and one blank sample (without leather) were exposed in parallel for all experimental conditions. Two different solutions were investigated, namely artificial sweat (ASW) (initial pH 6.5) and phosphate buffer (initial pH 8.0), as shown in Table 1. Phosphate buffer is the extraction solution stipulated in the standard (26), whereas ASW, according to EN 1811:2011 (36), is considered to be of higher relevance for skin exposure.

To investigate the effect of repeated exposure, a sequential exposure was conducted, denoted '1 + 1 + 1 hr' in Table 1, and compared with a continuous 3-hr exposure. In the sequential exposure, identical triplicate samples were exposed in three consecutive fresh solutions, for 1 hr in each (50 ml each, as for the non-sequential exposure). Each solution was analysed separately, denoted '1st hr, 2nd hr, 3rd hr' in Fig. 2. Membrane filtration as a solid–liquid separation technique has previously been shown to cause artefacts related to other metals (zinc and copper) in trace concentrations (37). The comparison between membrane filtration and centrifugation (704 relative centrifugal force) as separation techniques showed no significant differences in measured Cr concentrations under given conditions in the investigated samples

Table 1. Experimental conditions stipulated in the ISO 17075 protocol (26) and conditions used in this study of chromium release from leather

Parameters	ISO 17075	This study
Leather preparation	Powdered (by SiC grinding), undefined surface area	Whole surfaces of defined geometrical surface areas; small pieces, cut into sizes of approximately $2 \times 2 \times 1$ mm^3
Extraction solution	Phosphate buffer: 22.8 g/l $K_2HPO_4.3H_2O$, adjusted to pH 8.0 ± 0.1 with phosphoric acid; de-aeration	Phosphate buffer: 22.8 g/l $K_2HPO_4.3H_2O$, adjusted to pH 8.0 ± 0.1 by phosphoric acid; no de-aeration (all samples) and de-aeration (only $Cr^{Cr}{}_{gloves}$ and Veg^{veg}) Artificial sweat (all samples): 5.0 g/l NaCl, 1.0 g/l urea, 1.0 g/l lactic acid (pH 6.5 ± 0.05 with NaOH); no de-aeration
Extraction time period	3 hr	1, 3, 8 and 168 hr (all samples) 1 + 1 + 1 hr [repeated exposure of the same leather samples ($Cr^{Cr}{}_{gloves}$ and Veg^{veg})]
Extraction agitation	50–150 per min (gentle agitation, smooth circular movement)	22 cycles per min, 12° bi-linear agitation
Extraction temperature	Not defined	20–25°C (all samples); 30°C ($Cr^{Cr}{}_{gloves}$ and Veg^{veg}); 45°C ($Cr^{Cr}{}_{gloves}$ and Veg^{veg})
Sample mass to solution volume ratio	2 g/100 ml (0.2 g/l)	1 g/50 ml (0.2 g/l)
Solution aeration	De-aerated by purging with nitrogen for ~5 min prior to exposure, closed vessels during exposure	Aerated, closed vessels (all samples)[a]; de-aerated by purging with nitrogen for ~5 min prior to exposure, closed vessels during exposure ($Cr^{Cr}{}_{gloves}$ and Veg^{veg})
Solid–liquid separation	Membrane filtration (polytetrafluoroethylene or nylon) 0.45 μm	Centrifugation (all samples)[a] Membrane filtration (Supor, 0.2 μm, non-acid-cleaned[b]) ($Cr^{Cr}{}_{gloves}$ and Veg^{veg})
Liquid sample preparation	Solution transferred through cartridges filled with reverse phase (removal of interfering dyes)	Acidified (AAS analysis); frozen prior to analysis (spectrophotometry)
UV irradiation and visible light conditions	Conditions not defined; no UV irradiation	Darkness (all samples)[a]; 15-W UV lamp ~25 cm above the leather samples in solution (open vessels) ($Cr^{Cr}{}_{gloves}$ and Veg^{veg})

AAS, atomic absorption spectroscopy; UV, ultraviolet.
[a]Standard conditions for most results presented in this article, if not indicated otherwise.
[b]Lowest risk for contamination and adsorption found for Ni, Cu and Zn in (37).

(File S1, Table S1). The membrane filter used was a polyethersulfone membrane from Acrodisc with the trade name Supor, supplied by VWR, Stockholm, Sweden, had a pore size of 0.2 μm, a polypropylene housing (Ø 25 mm), and was recommended for trace element analysis in (38). This suggests that both techniques could be used within this context.

Cr speciation analysis

The total Cr content in acidified solution samples was determined by means of flame atomic absorption spectroscopy with 0 (ultrapure water), 0.5, 1.5, 5, 10, 15 and 45 mg/l Cr (in 1% HNO_3) as calibration standards. Quality controls of known concentration were measured after at least every fifth sample, and the instrument was re-calibrated when the measured concentration deviated by >10% from the nominal concentration. The limit of detection in the samples was estimated to 0.015 mg/l (three times the highest standard deviation of the blank samples), and the limit of determination was estimated to be 0.05 mg/l (10 times the standard deviation). All reported Cr concentrations were significantly above the limit of determination. The Cr(VI) concentration in non-acidified solution samples (frozen prior to determination) was determined via the formation of a pink complex formed with diphenylcarbazide (39), spectrophotometrically measured at 540 nm. Calibration samples were prepared from the blank extraction/exposure solution (ASW or phosphate buffer) and known concentrations of Cr(VI). All samples, phosphoric acid (70 vol.%) and the diphenylcarbazide solution (1.0 g of 1,5-diphenylcarbazide in 100 ml of acetone acidified with one drop of glacial acetic acid) had the same volume ratio as stipulated in ISO 17075 (26), corresponding to 96 vol.% sample, 2 vol.% phosphoric acid, and 2 vol.%

diphenylcarbazide solution, respectively. The calibration standards were prepared at concentrations of 0, 125, 250, 500 and 1000 µg/l Cr(VI). All calibration curves were linear ($R^2 = 0.9964–0.9999$). The limit of determination was estimated to be ~ 60 µg/l Cr(VI). All reported values exceeded the limit of determination.

All release data presented are normalized to the dry mass of the leather, $mg/kg_{leather}$ (1 $mg/kg_{leather}$ corresponds in this study to 0.02 mg/l for 1 g of sample), normalized to the leather geometric surface area, mg/cm^2 (1 mg/cm^2 corresponds in this study to 20 mg/l for a 1-cm^2 sample), and as average values of triplicate samples with the corresponding blank concentration, if positive, subtracted. The thickness of the dry leather samples ranged from 1 mm ($Cr^{Cr}{}_{gloves}$) to 2.5 mm (Cr^{veg}). Blank concentrations were below the limits of determination for Cr(VI) and for total Cr. Cr(III) was determined as the total Cr with any detected Cr(VI) subtracted.

Statistical analysis

To identify the statistical significance of observed differences in experimental findings, a Student *t*-test of unpaired data with unequal variance was employed between two different datasets. Differences are counted and denoted as 'significant' when $p < 0.05$, with higher significance for a smaller *p*-value.

Results

Effect of sample area (powdering)

The ISO 17075 standard test (26) stipulates abrasion of the leather to a powder to increase the investigated surface area. The influence of sample size on the release of Cr(III) and Cr(VI) was investigated for all four leathers by comparing whole surfaces (approximately 15–40 cm^2, depending on thickness) and finely cut pieces [as in (40, 41)] of the same leather (approximately 40–85 cm^2) of a total mass of 1 g, as shown in Fig. 1. The finely cut Cr-tanned samples all showed significantly ($p < 0.01$) increased amounts of released Cr(III) as compared with the whole surfaces. The $Cr^{Cr}{}_{gloves}$ showed a significant reduction ($p < 0.01$) in the ratio of released Cr(VI) to total released Cr (whole surface, 18.1%; finely cut pieces, 8.2%).

Effect of de-aeration

Both de-aerated and aerated conditions were investigated in this study. No significant differences were observed in the case of released Cr(III) or for the released fraction of Cr(VI) (per total Cr released). However, a significant

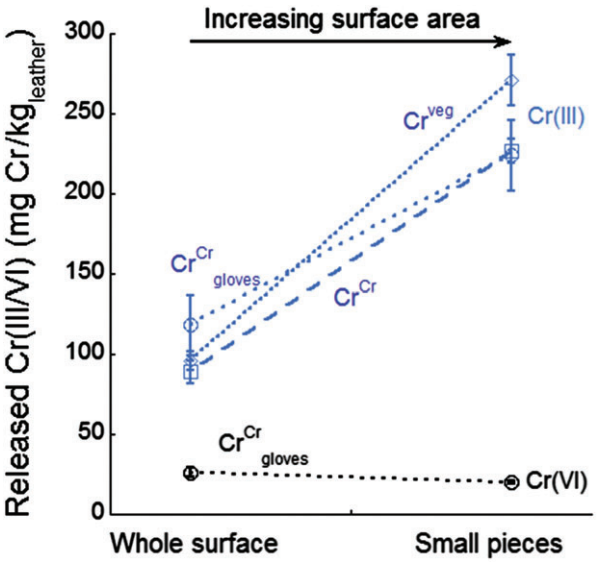

Fig. 1. Amounts of released Cr(III) (blue) and Cr(VI) (black) measured in phosphate buffer after 3 hr of exposure at 20–25°C for whole leather samples and finely cut pieces, both of a total mass of 1 g. The error bars show the standard deviation between triplicate samples. The amounts of released Cr(III) in solution were below the limit of detection for Veg^{veg}, as were the amounts of Cr(VI) released from the Cr^{Cr}, Cr^{veg} and Veg^{veg} samples. The dotted lines are only intended to provide guidance for the eye.

($p < 0.05$) reduction in released Cr(VI) was evident under de-aerated conditions as compared with aerated settings (File S1, Table S2).

Initial kinetics

The extraction time in the standardized test is stipulated as 3 hr. Figure 2 shows the amounts of Cr(III) and Cr(VI) released from the different samples into phosphate buffer after the first, second and third hour in sequence (1 + 1 + 1 hr) (identical triplicate samples exposed in three subsequent fresh solutions, 1 hr in each) as compared with a continuous 3-hr exposure (0–3 hr). The amounts of Cr(III) released were significantly reduced ($p < 0.0001$) between the first hour and the second hour of exposure, whereas no significant difference was observed between the second hour and the third hour of exposure (Fig. 2a). Similar observations were made for the release of Cr(VI) (first hour to second hour: $p < 0.05$, non-significant changes between the second hour and third hour) (Fig. 2a). The pH of the phosphate buffer solution dropped predominantly during the first hour of exposure, to a significantly ($p < 0.01$) lower extent than during the second hour and the third hour ($p < 0.05$ as compared with the second hour) of

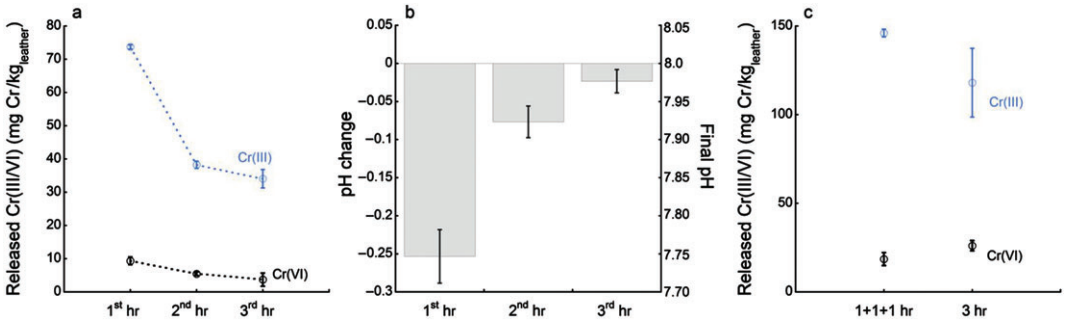

Fig. 2. Amounts of released Cr(III) (blue) and Cr(VI) (black) normalized to dry leather mass (a) and corresponding changes in solution pH (b) of $Cr^{Cr}{}_{gloves}$ in phosphate buffer (20–25°C) for triplicate samples subsequently exposed for three 1-hr periods (1 + 1 + 1 hr) without drying between each period (<1 min), as compared with triplicate samples continuously exposed for 3 hr (c). The dotted lines in (a) are only intended to provide guidance for the eye.

exposure (Fig. 2b). The pH drop during the first hour of exposure (−0.26 pH) was comparable ($p = 0.58$) to the pH change observed for the continuous 3-hr exposure (−0.28 pH). No significant differences in amounts of released Cr(III) ($p = 0.13$) were observed between the sum of the sequential exposure (1 + 1 + 1 hr) and the continuous 3-hr exposure. However, significantly more ($p < 0.05$) Cr(VI) was released during the continuous 3-hr exposure than during the sequential exposure (Fig. 2c). Similar trends were observed for the release of Cr(III) and Cr(VI) normalized to the surface area (File S1, Figure S1).

Cr release for 1 week in ASW

The kinetics of Cr release into ASW were investigated for 1, 3, 8 and 168 hr of exposure of whole leather samples (15–40 cm^2) under conditions simulating prolonged contact with the skin, for example shoes or working gloves (Fig. 3). Cr(III), but not Cr(VI), was released from all leather samples when they were exposed to (immersed in) ASW. Cr(III) was released in relatively large amounts, and continued to be released even after 3 hr of exposure. The largest Cr(III) release was observed from $Cr^{Cr}{}_{gloves}$, with > 3000 $mg/kg_{leather}$ after 168 hr of exposure. The $Cr^{Cr}{}_{gloves}$ sample was the thinnest sample, and hence had the largest surface area per mass among the samples investigated (Fig. 3a). When normalized to the exposed geometrical surface area, the release of Cr(III) did not differ significantly between the Cr-tanned samples (Fig. 3b). The release rate (Fig. 3c) was highest ($p < 0.05$ as compared with Cr^{Cr} after 1 and 8 hr, and Cr^{veg} after 8 hr) for $Cr^{Cr}{}_{gloves}$ up to 8 hr of exposure, but highest ($p < 0.05$) for Cr^{Cr} after 168 hr of exposure. All samples showed relatively similar Cr release rates (0.00031–0.00045 $mg/cm^2/h$) after 168 hr (1 week), but differences in initial kinetics (Fig. 3c). The solution pH was reduced during exposure of all leather samples (Fig. 3d), with a larger reduction for longer durations, and reached a final pH of 4.4, at the lowest, which is the natural pH of tanned leather (42).

Effect of temperature and ultraviolet (UV) irradiation at wet exposure

The influence of temperature on the release of Cr(III) and Cr(VI) was investigated for $Cr^{Cr}{}_{gloves}$ in ASW. An increase in temperature from ambient laboratory temperature up to 45°C increased the release of Cr(III) in ASW significantly ($p < 0.01$, factor of 3.3) (Fig. 4a). Similar findings (a factor of 1.6) were observed between ambient room temperature and 30°C (approximate non-occluded skin temperature), being non-significant ($p = 0.07$) when normalized per dry mass (Fig. 4a), but significant ($p < 0.05$) when normalized to surface area (File S1, Figure S2). As judged from the large pH drop at higher temperatures (Fig. 4b), other leather constituents, including acids, were released to significantly higher extents at higher temperatures. This trend was significant ($p < 0.05$) for both $Cr^{Cr}{}_{gloves}$ and Veg^{veg} for all temperatures investigated (Fig. 4b). As no Cr(VI) was released and measured in solution from $Cr^{Cr}{}_{gloves}$ in the acidic (pH 4.4–6.5) ASW, the effect of UV irradiation was investigated while the sample was immersed in phosphate buffer (Fig. 4c,d) at a solution temperature of 20–25°C. UV irradiation did not induce any significant changes ($p > 0.05$) in Cr(III) or Cr(VI) release, or solution pH (Fig. 4c,d). Similar trends were observed when Cr release was normalized to the surface area (File S1, Figure S2).

Discussion

This study shows that several test parameters of the ISO 17075 affect the amount of detected Cr(VI). Cutting/grinding of the sample, as required by the test protocol, could possibly result in an underestimation

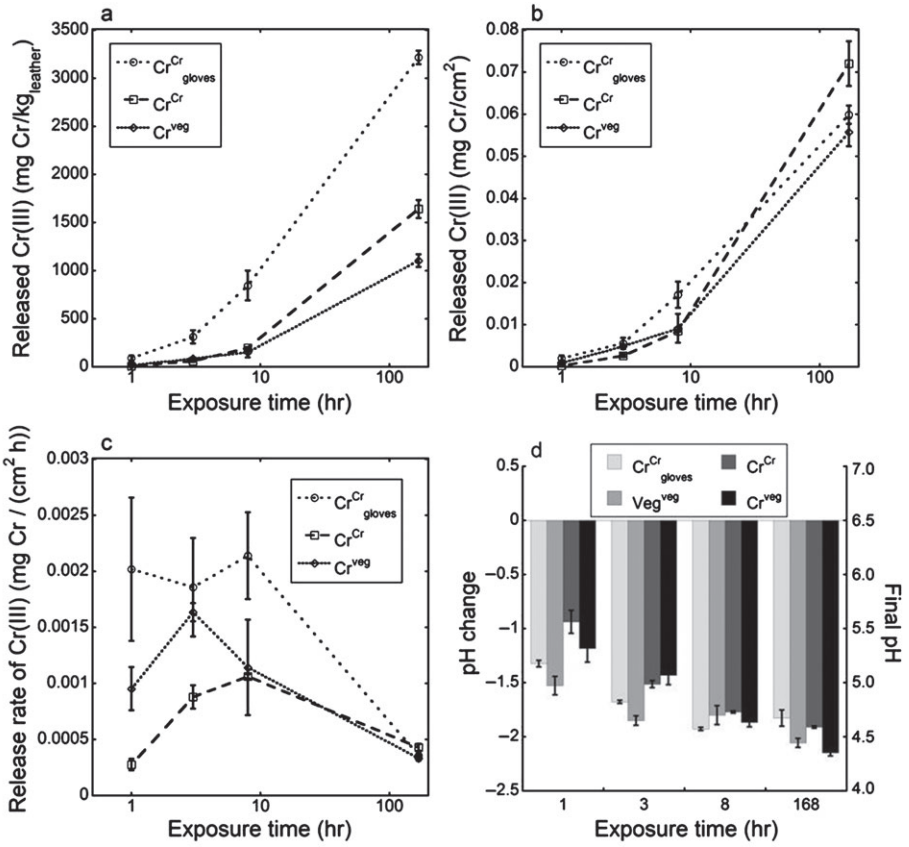

Fig. 3. Amounts of released Cr(III) normalized to dry leather mass (a), surface area (b), and surface area and exposure time [release rate (c)], and corresponding solution pH changes (d), in artificial sweat, initial pH 6.5, 20–25°C, whole (non-cut) surfaces after 1, 3, 8 and 168 hr of exposure. The amounts of Cr released and measured in solution from the vegetable-tanned leather sample (Veg^{veg}) were below the limit of detection in all cases. The error bars represent the standard deviation for triplicate samples. The dotted lines are only intended to provide guidance for the eye.

of the release of Cr(VI); however, this should be further investigated. As expected, an increased surface area, as provided by finely cut pieces, resulted in an increased amount of released Cr(III). The reduced amount of released Cr(VI) analysed in solution is most likely a result of the parallel release of acids and/or reducing agents from the leather (43). It could also be related to a lower Cr(VI) content in the inner parts of the leather (44, 45).

The ISO 17075 protocol stipulates that the extraction solution (phosphate buffer) should be de-aerated during exposure to avoid oxidation of any released Cr(III) by dissolved oxygen. However, such conditions are not necessarily relevant for skin or environmental exposure. The phosphate buffer as extraction solution and its reduced dissolved oxygen content (de-aerated conditions) stipulated by ISO 17075 (26) have been highly debated in terms of its potential to oxidize any released Cr(III) (24, 41). However, non-significant differences in the ratio of Cr(III) and Cr(VI) released into solution were observed in this study when parallel exposures in aerated and de-aerated phosphate buffer solutions were compared. Similar findings have been reported in the literature (41). The oxidation by radicals from certain lipids in leather can increase the amount of Cr(VI) detected in phosphate buffer (41, 42, 44, 46–51). Released reducing species can, on the other hand, reduce the Cr(VI) content in phosphate buffer (43). It must hence be emphasized that the standard test protocol may not reflect the total Cr(VI) content of the leather sample (42).

One of the major challenges in the determination of Cr(VI) released from leather products by the use of spectrophotometry is the colouring of the extraction solution caused by the release of leather constituents, tanning chemicals, and/or dyes. Different solid-phase extraction techniques have been described in the literature, and preparation steps have been suggested. However, none of these suggestions guarantees a high accuracy and lack of artefacts for any kind of leather material (28, 42–44, 52, 53).

The ISO 17075 standard does not consider the influence of temperature and UV irradiation, which are parameters of relevance for skin contact. The effects of temperature and UV irradiation have mostly been investigated in the literature for Cr(VI) in leather under dry conditions (heating or UV irradiation under dry conditions). Heating (often > 80°C) during leather manufacture or processing (e.g. shoe making) may increase the amount of Cr(VI) in the leather in the presence of certain fatty acids

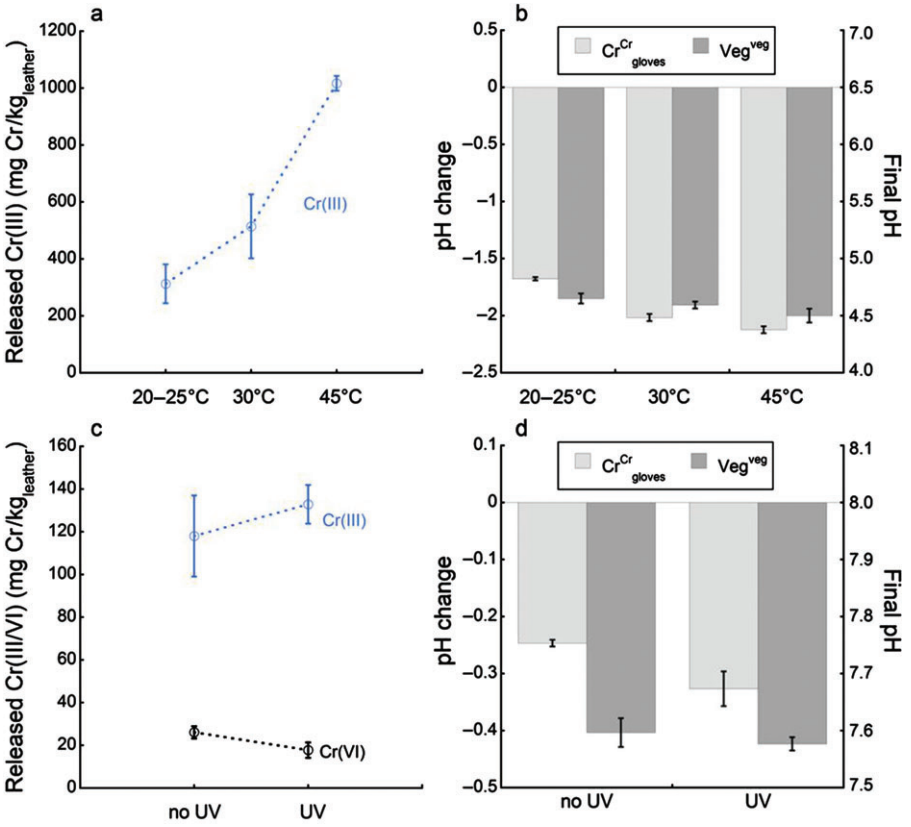

Fig. 4. Amounts of released Cr(III) (blue) and Cr(VI) (black) in solution and normalized to dry leather mass (a, c), and corresponding changes in solution pH (b, d), of $Cr^{Cr}{}_{gloves}$ and Veg^{veg} in artificial sweat (ASW) (a, b) and phosphate buffer (c, d) after 3 hr at 20–25°C, 30°C, and 45°C (a, b), or at 20–25°C [no ultraviolet (UV) irradiation as compared with UV irradiation] (c, d). Released Cr(III) and Cr(VI) concentrations in solution were below the limit of detection for Veg^{veg}, and the Cr(VI) concentration was below the limit of detection for $Cr^{Cr}{}_{gloves}$ in ASW (a). The dotted lines in (a) and (c) are only intended to provide guidance for the eye.

and atmospheric oxygen (28, 41, 45, 54–58). Similar trends have been observed for UV-irradiated leather in the presence of certain fatty acids and oxygen under dry conditions (28, 41, 44, 45, 54, 56, 58, 59). Shoe making, which involves both dry heating and, sometimes, alkaline glues, can trigger the formation of Cr(VI) in leather (57). In this study, the effects of both temperature and UV irradiation (aiming to mimic skin and outdoor exposure), which are parameters known to suppress the formation of Cr(VI), were investigated under wet conditions (53). The observed differences between wet and dry conditions (literature findings) in terms of the release and formation of Cr(VI) in leather are expected, as longer duration of storage at a relative humidity exceeding 35%, increased relative humidity and increased water content in the leather are conditions known to reduce the Cr(VI) content (41, 42, 60).

In this study, it was shown that the geometrical surface area of leather exposed to the solution is a more relevant parameter than the leather dry mass for normalization of release data. The results indicate that Cr release is limited by diffusion processes, at least when the leather is immersed in the same solution.

It has been stated that all extractable Cr(VI) in the leather is released during the first 3 hr (42). Our results indicate, however, that 3 hr may, in some cases, be too short for all Cr(VI) present in the leather to be released. This is indicated for Cr(VI) released during the sequential exposures (1 + 1 + 1 hr, in total 3 hr), for which the released concentrations were well above the detection limit also during the last hour of the sequential exposure. The results suggest that Cr(VI) might still be released after 3 hr in the case of leather with high extractable amounts of Cr(VI) (as in this study). It is of importance for further discussions on allergic Cr contact dermatitis to consider that the release of, for example, acids from the leather is also time-dependent, and predominantly takes place during the first hour of exposure. This might be important for repeated skin contact, as these acids may be able to reduce any released Cr(VI) (43), an ability that is possibly lost after long-term repeated exposure.

The available literature data suggest significantly higher release of Cr(III) than of Cr(VI) (21, 40, 45, 61), as confirmed in this study. This is also in agreement with other studies investigating the release of Cr(III) and Cr(VI) from Cr-tanned leather (20, 21, 40, 45, 61). It is considered less likely that Cr(VI) will be released in sweat and under conditions of prolonged skin contact, unless the leather is exposed to a very dry environment, UV irradiation, and/or oxidizing or alkaline species. The amount of

Cr(VI) released from Cr^{Cr}_{gloves} (at most 26.1 $mg/kg_{leather}$) in the present study is among the higher values reported in the literature (< 1–96 $mg/kg_{leather}$) (19–22, 41). Nevertheless, no Cr(VI) was observed to be released from that leather into ASW, which is in agreement with previous studies (42, 43, 62). Prolonged (> 3 hr) exposures in ASW showed that Cr(III) would be, by far, the predominant released species. Even though alarming reports exist on the significance of Cr(III) in leather for the increasing prevalence of Cr allergy (22, 29, 63), Cr(III) is not addressed in the EU limitation on Cr in leather that will enter into force in 2015. This may, to some extent, be explained by the general awareness of Cr(VI) as an important allergen, the current use of potassium dichromate [Cr(VI)] in diagnostic patch testing, and the significantly lower concentration of Cr(VI) (as dichromate) than of trivalent chromium compounds that is required to induce dermatitis in Cr-allergic patients (29, 64, 65).

Conclusions and Future Perspectives

1 Significantly more Cr(III) than Cr(VI) was released for all conditions and investigated leather samples.
2 There is a possibility that the measured amounts of released Cr(VI) in the extraction solution are underestimated when the leather sample is ground or cut into small pieces as compared with whole leather surfaces, owing to the parallel release of reducing species from the leather. This requires further investigation.
3 The temperature was shown to substantially influence the release of Cr in ASW. It is suggested that this parameter should be investigated to determine whether it should be defined in the ISO 17075 test protocol.
4 The Cr speciation in solution was shown to be extremely dynamic and influenced by a large number of leather, solution and environmental parameters.
5 Corresponding effects on the release of Cr(III) are essentially unexplored, and need to be considered in future studies.
6 Several conditions, such as prolonged and repeated skin exposure to Cr-tanned leather, relative humidity and water content in the leather, UV irradiation, and heat, may change the extent and oxidation form of released Cr and the reducing capacity of reducing leather-specific agents released in parallel. Some of them are investigated in Part II of this study, and further studies should also investigate the amount of Cr actually deposited on the skin during contact with Cr-tanned leather.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

File S1. Chromium released from leather – I: exposure conditions that govern the release of chromium(III) and chromium(VI).

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