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A quantitative assessment of risks of heavy metal residues in laundered shop towels and their use by workers

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ABSTRACT

This paper presents a risk assessment of exposure to metal residues in laundered shop towels by workers. The concentrations of 27 metals measured in a synthetic sweat leachate were used to estimate the releasable quantity of metals which could be transferred to workers' skin. Worker exposure was evaluated quantitatively with an exposure model that focused on towel-to-hand transfer and subsequent hand-to-food or -mouth transfers. The exposure model was based on conservative, but reasonable assumptions regarding towel use and default exposure factor values from the published literature or regulatory guidance. Transfer coefficients were derived from studies representative of the exposures to towel users. Contact frequencies were based on assumed high-end use of shop towels, but constrained by a theoretical maximum dermal loading. The risk estimates for workers developed for all metals were below applicable regulatory risk benchmarks. The risk assessment for lead utilized the Adult Lead Model and concluded that predicted lead intakes do not constitute a significant health hazard based on potential worker exposures. Uncertainties are discussed in relation to the overall confidence in the exposure estimates developed for each exposure pathway and the likelihood that the exposure model is under- or overestimating worker exposures and risk.

1. Introduction

The use of reusable, natural-fiber-based towels in the workplace as rags for wiping engine or mechanical parts, work surfaces, or equipment gives rise to the possibility of some residual presence of metallic constituents in the towels despite the laundering process. Concentrations of metals in samples of laundered shop towels were reported previously in a paper that also presented a screening risk evaluation for workers using the towels (Beyer et al., 2003, 2010). The present effort was undertaken to perform a refined evaluation of the health risks associated with residual metals in laundered shop towels using analytical methods that provide more relevant measures of the available metal concentrations and applying alternative models for evaluating exposure and risk. The study of these exposures was not prompted by any known or reported health effects in workers using shop towels. Rather, it was prompted by the publication of the previous work suggesting that metals may be present on used shop towels at levels that exceed established regulatory toxicity criteria. Since the current manuscript was drafted, Beyer and co-workers (Beyer et al., 2014) have additional analytical data using the same screening level analytical methods and have repeated their suggestions that metals are present at levels exceeding conservative toxicity criteria, but the chemical methods and risk assessment approaches used have not been refined and remain screening level approaches.

Quantifying chemical constituent exposures that may result from the handling of garments, tools, accessories, or other consumer products has typically been conducted using *ad hoc* models that are tailored to the chemical constituents of interest, the nature of the exposure medium, and the circumstances of contact between the user (receptor) and the consumer product. No single model has been established that is intended to fit all types of situations, although several examples can be found in the literature representing efforts prompted by consumer right-to-know initiatives (e.g., California's Proposition 65) and by consumer safety protection agencies (CPSC, 1997, 2006, 2010; Cal-EPA, 2008, 2011).

Exposure models that have been most commonly applied to the prediction of human exposures to organic chemicals that might be present in clothing or household materials across a broad range of scenarios and circumstances are often called transfer models. A transfer model begins with a surface concentration of a chemical that is assumed to be releasable or dislodgeable and assumes a fractional transfer to the hands of the user based on values obtained from the literature or experiments simulating the

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exposure conditions. Transfer models have been used extensively in modeling human exposures to pesticides, which have been impregnated into garments or applied to a carpet or other surface (Lu and Fenske, 1999; Zartarian et al., 2000; Zeilmaker et al., 1999) and other contacted surfaces, including fabrics (Snodgrass, 1992; Yang and Li, 1993; Camann et al., 1996; Brouwer et al., 1999; Rodes et al., 2001; Cohen Hubal et al., 2005, 2008). Transfer models are also used to estimated exposures to metals from hard surfaces like floors and office furniture (DiBiasio and Klein, 2003; USACHPPM, 2009). Similar to the Beyer et al. (2003, 2010, 2014) assessments, a transfer model was applied to the assessment of exposure to the residual metals in shop towels in this assessment. However, significant advancements to the overall transfer model are employed in this assessment of shop towel exposures, which include (1) employing methods of analysis that provide a concentration of the available (dislodgeable) concentration of each metal, and (2) placing limits on the concentration of metals that can possibly accumulate on the skin surface. The limiting assumption, based on measurement data, is that the concentration of a substance that may accumulate on a hand will not exceed the surface concentration on the contact material. For soft surfaces like carpet or garment fabrics, the pickup by a hand is never observed to exceed the concentration of the substance on the material itself, even after multiple contacts (Yang and Li, 1993; Camann et al., 1996; Brouwer et al., 1999; Rodes et al., 2001; Cohen Hubal et al., 2005, 2008).

The simplest screening-level analysis of the metal concentrations associated with fabric, such as shop towels, is the measurement of total mass by weight ("bulk analysis"), using acid digestion. For the purposes of risk assessment, such data fail to measure the available surface concentration of each metal that is relevant to human exposure. As the basis for a more refined risk assessment, data on the available metal concentrations were obtained using a leachability test protocol with a synthetic sweat solution to simulate conditions of contact of human skin with a towel.

Leachability testing protocols have been used as the basis for risk assessment by evaluations of medical devices such as bandages, first aid dressings, and gloves (Seibersdorf, 1998), flame retardants in upholstered materials (CPSC, 2006), cadmium and lead in children's toys (CPSC, 1997), and dyes contained in toys and other articles handled by children (Zeilmaker et al., 1999), among others. The use of leachability data may raise the question of whether it is necessary to make an adjustment for the transfer efficiency governing the transfer of metals from towel to hand. The estimates of transfer efficiencies from the literature studies cited above have measured the transfer of chemicals that were 100% available. Thus, transfer efficiency is a relevant input parameter for available metals in shop towels. In addition, risk assessments of contact with metals on hard surfaces have used very similar transfer efficiency values (DiBiasio and Klein, 2003; USACHPPM, 2009).

This risk assessment of workers was developed to provide a conservative, but reasonable prediction of risks associated with the use of shop towels. It is based on a high-end, but reasonable level of towel usage. Exposure factors and other assumptions were chosen to represent a mix of average- and upper-bound levels of anticipated worker exposure as is consistent with a Reasonable Maximum Exposure scenario.

The uncertainties in this assessment are discussed in detail in the uncertainty section where the effect of using alternative exposure factor values and assumptions regarding worker exposure on the overall confidence in the estimated risks and hazard indices is evaluated. The discussion of uncertainties focuses on several elements of the risk assessment that make a substantial contribution to uncertainty in the results. These were related to both the methods used to obtain and interpret the analytical data and the model used to quantify exposure.

2. Methods

2.1. Data collection

Laundered shop towels were obtained from 10 different rental/laundering facilities and forwarded to Exova laboratories (Santa Fe Springs, CA) for analysis of metals. Each facility provided a bundle of 10 towels from which a composite sample was prepared, such that a single analytical result would be obtained for each towel bundle. Composite samples were obtained by collecting large cut-outs (approximately 8 × 10″ in size and representing approximately 50% of the towel area) from individual towels. These sections were minced into small (~1 cm^2) bits with ceramic scissors and mixed thoroughly prior to the collection of subsamples for the analyses of metals.

Leachability tests were performed on the composite towel samples using synthetic sweat solution per AATCC, 2011, a method for measuring the leaching of fabric dyes under simulated conditions of use and specifically, the effects of acidic perspiration. The synthetic sweat solution was prepared by adding sodium chloride (10 g), lactic acid (1 g), disodium phosphate (1.875 g), and histidine (0.25 g) to 1 L of deionized water (AATCC, 2011). A 200 mL volume of this solution was mixed with 20 g of the homogenized sample and placed in a water bath at 37 °C for 1 h with mild agitation. Leachates were treated with concentrated nitric acid (0.1 mL into 10 g of leachate) to solubilize the substances leaching from the samples. Internal standards were added to these leachates, and concentrations of 27 metals see (Table 1) were measured by inductively-coupled plasma-mass spectrometry, based on an Exova Standard Operating Procedure (SOP No. 7040, Revision 12). The solubilization step with nitric acid overestimates the available concentration if metal particles are present in the synthetic sweat solution, because these particles would not likely be available for transfer to skin during towel use.

2.2. Available metal concentrations in towels (C_{towel})

The leachable concentration of each metal was determined by multiplying the reported leachate concentration (in μg/g) by the leachate volume (200 mL) and dividing by the towel sample weight (20 g). Multiplying this value by the towel area density (measured to be 0.026 g/cm^2) results in a leachable concentration per unit surface area of towel (in μg/cm^2). Based on these data (Table 1), a 95% upper confidence level (UCL) on the mean concentration was developed to represent the average exposure concentration for use in the risk assessment. When a metal was detected in fewer than three samples, the maximum detected concentration was used *in lieu* of a 95% UCL. The concentration term is represented as C_{towel} in the exposure model presented below. A reference towel sample, which was a new, unlaundered towel, was similarly analyzed; results of this analysis are also presented in Table 1. These results overestimate the true available concentrations of metals per unit surface area of towel, because the leachate method solubilized metals from the surface of the fabric as well as metals from deeper in the nap of the towel. The latter would not actually be available for transfer to skin during towel use.

2.3. Exposure model

As described above, the basic approach to the modeling of exposure in this assessment is characterized as a *transfer* model, which uses transfer coefficients to describe the towel-to-hand or

Table 1
Data summary for synthetic sweat leachate analysis: selected metals.

Constituent	Detected concentrations (μg/g)						
	Total detected	Reference sample (μg/g)	Minimum	Maximum	Mean	Standard deviation	95% UCL
Aluminum	10/10	0.14	0.024	0.5	0.131	0.045	0.358
Antimony	10/10	0.008	0.014	0.2	0.0567	0.043	0.0958
Arsenic	10/10	0.0057	0.0013	0.01	0.00332	0.00205	0.00511
Barium	10/10	0.18	0.015	1.4	0.434	0.335	0.801
Beryllium	6/10	<0.00004	0.00009	0.001	0.000337	0.00024	0.000478
Boron	8/10	0.07	0.05	0.76	0.196	0.135	0.469
Cadmium	10/10	0.0004	0.0078	1.6	0.27	0.057	0.94
Calcium	10/10	67	24	77	47.4	42	57.9
Chromium	10/10	<0.001	0.002	0.19	0.0251	0.005	0.105
Cobalt	10/10	0.00047	0.005	0.33	0.109	0.069	0.173
Copper	10/10	0.012	0.35	6	2.48	1.75	3.43
Iron	10/10	0.13	0.057	3.3	0.564	0.19	1.95
Lead	10/10	0.00054	0.0012	0.028	0.0105	0.00755	0.0205
Magnesium	10/10	26	3.6	25	11.5	11.5	15.3
Manganese	10/10	0.36	0.21	0.81	0.449	0.39	0.555
Mercury	2/10	<0.0001	0.0002	0.0003	0.00025	0.00025	NA
Molybdenum	10/10	0.0009	0.00615	0.68	0.11	0.0555	0.389
Nickel	10/10	0.0034	0.044	1.4	0.261	0.0715	0.87
Potassium	10/10	9.2	0.6	8.4	2.86	2.2	4.21
Selenium	1/10	<0.001	0.006	0.006	0.006	0.006	NA
Silver	5/10	<0.00005	0.00011	0.00048	0.000299	0.000315	0.0000292
Strontium	10/10	2.2	0.19	2	0.56	0.395	0.938
Thallium	5/10	<0.00006	0.0001	0.00018	0.000122	0.00011	0.000127
Tin	10/10	0.013	0.00058	0.019	0.00405	0.0019	0.00806
Titanium	6/10	0.004	0.002	0.008	0.004	0.003	0.0045
Vanadium	9/10	<0.0002	0.0004	0.0022	0.00101	0.0009	0.00125
Zinc	10/10	0.049	1.6	11	5.23	4.7	6.91

Notes:
UCL, upper confidence limit.
NA, UCL was not calculated for metals with less than five detected samples. Maximum detected concentration was used.
<, metal detected below laboratory detection limit.
A substitution equal to 1/2 of the detection limit was used for samples/analytes with undetectable results for the purpose of calculating a mean, standard deviation, and 95% UCL.
All summary statistics and 95% UCLs were calculated using ProUCL Version 4.1.
Laboratory method: synthetic sweat leachate by SOP 7040, Rev 12.
Duplicate sample processing was performed as follows:
– Both values non-detect: select the minimum value.
– One detect / one non-detect: select the detected value.
– One non-detect / one non-reported: select non-detect value.
– One detect / one non-reported: select detect value.
– Both detects: compute arithmetic mean.

hand-to-face transfer of metals, together with estimates of the expected frequency and/or duration of each contact. The chosen model was adapted from models found in the open literature and in regulatory guidance, based on all foreseeable exposure pathways for workers using shop towels. An *available* (dislodgeable) concentration of each metal in the towels was the source term for the exposure model. The model used elements of existing exposure models that are applied to risk assessments for various impurities or residues in consumer products (Cal-EPA, 2011; CPSC, 2006; EBRC, 2007; Zeilmaker et al., 1999).

The exposure model for workers focused on three potential exposure pathways, each giving rise to a portion of the metal assumed to be ingested. These pathways include: exposure via towel-to-hand contact and subsequent hand-to-mouth contact, towel-to-hand contact and subsequent hand-to-food contact, and direct contact of the towel with the mouth. In modeling hand-to-mouth transfer, contact with the mouth is based on the incidental but predictable hand-to-face contact that occurs throughout the day. The towel-to-mouth pathway addresses the possible contact of the towel directly with the mouth, although the use of a shop towel to wipe the mouth unlikely to occur on a regular basis. It is further assumed that these three exposures could all occur throughout a work day, and therefore, a total exposure estimate was evaluated based on all three pathways.

This assessment addressed dermal contact only as a pathway of subsequent oral exposures via hand-to-mouth contact. The focus on oral exposures versus dermal absorption exposures is due to the fact that the dermal absorption of metals is very low, particularly when in a non-aqueous medium or in an elemental, non-ionic form. Even metal salts have dermal absorption factors that are generally much less that 1%, or even less than 0.1% (EBRC, 2007; US EPA, 2004). In cases where contact with a material is intermittent, but there is the chance that the transferred substance can remain on the skin after contact, hand-to-mouth transfers (and subsequent ingestion) are more important than dermal absorption and the focus on this pathway is justified (Cal-EPA, 2011; CPSC, 2010; Dubé et al., 2004). However, to test this assumption, dermal absorption was assessed for select metals using the towel leachability data and the United States Environmental Protection Agency (US EPA) (2004) model for estimating a dermal applied dose, with corresponding dermal permeability coefficients for constituents in an aqueous medium. The results confirmed that dermal absorption as an exposure pathway would represent a negligible (<1%) contribution to overall dose in workers, as compared to hand-to-mouth transfer.

The exposure model for the three exposure pathways is represented by the equation below. Each results in a daily dose in units of mg/kg-day.

2.3.1. Towel-to-hand-to-mouth exposure

$$\mathrm{Dose} = \sum_{n=1}^{n=\mathrm{CF_{HM}}} [\mathrm{C_{HAND}}(n) \times \mathrm{TE_{HM}}] \times (\mathrm{SA_{HM}} \times \mathrm{FI_H} \times \mathrm{EF} \times \mathrm{ED}) \div (\mathrm{AT} \times \mathrm{BW}) \qquad (1)$$

where:

Dose = average daily dose (ADD); lifetime ADD (LADD) for carcinogens (mg/kg-day).
$C_{HAND(n)} = C_{HAND(n\text{-}1)} \times (1 - TE_{HM})$ (mg/cm^2).
$C_{HAND(n=1)} = C_{towel} \times (0.001\ \mathrm{mg}/\mu\mathrm{g}) \times TE_{TH} \times CF_{TH}$ (mg/cm^2).
CF_{HM} = hand-to-mouth contact frequency (number of contacts per day).
C_{towel} = available concentration of metal on surface of towel (μg/cm^2).
TE_{TH} = transfer efficiency, towel-to-hand (fraction).
CF_{TH} = towel contact frequency (number of contacts per day).
TE_{HM} = transfer efficiency, hand-to-mouth (fraction).
SA_{HM} = surface area of skin (hand) in contact with mouth (cm^2).
FI_H = fraction ingested from hand to mouth contact (fraction).
EF = exposure frequency (days per year).
ED = exposure duration (years).
AT = averaging time (days).
BW = body weight (kg).

2.3.2. Towel-to-hand-to-food exposure

$$\mathrm{Dose} = [\mathrm{C_{HAND(1)}} + \mathrm{C_{HAND(10)}}] \times (\mathrm{TE_{HF}} \times \mathrm{SA_{HF}} \times \mathrm{FI_F} \times \mathrm{EF} \times \mathrm{ED})/\mathrm{AT} \times \mathrm{BW} \qquad (2)$$

where:

Dose = average daily dose (ADD); lifetime ADD (LADD) for carcinogens (mg/kg-day).
$C_{HAND(n)} = C_{HAND(n\,-\,1)}\ (1 - TE_{HM})$ (mg/cm^2).
$C_{HAND(n=1)} = C_{towel} \times (0.001\ \mathrm{mg}/\mu\mathrm{g}) \times TE_{TH} \times CF_{TH}$ (mg/cm^2).
C_{towel} = available concentration of metal on surface of towel (μg/cm^2).
TE_{TH} = transfer efficiency, towel-to-hand (fraction).
CF_{TH} = towel contact frequency (number of contacts per day).
TE_{HF} = transfer efficiency, hand-to-food (fraction).
CF_{HF} = food contact frequency (number of contacts of hands with food per day) (see text).
SA_{HF} = surface area of skin (hand) in contact with food (cm^2).
FI_F = fraction ingested from food (fraction).
EF = exposure frequency (days per year).
ED = exposure duration (years).
AT = averaging time (days).
BW = body weight (kg).

2.3.3. Towel-to-mouth exposure

$$\mathrm{Dose} = \mathrm{C_{towel}} \times (0.001\mathrm{mg}/\mu\mathrm{g}) \times \mathrm{TE_{TM}} \times \mathrm{CF_{TM}} \times \mathrm{SA_M} \times \mathrm{FI}_T \times \mathrm{EF} \times \mathrm{ED}/\mathrm{AT} \times \mathrm{BW} \qquad (3)$$

where:

Dose = average daily dose (ADD); lifetime ADD (LADD) for carcinogens (mg/kg-day).
C_{towel} = available concentration of metal on surface of towel (μg/cm^2).
TE_{TM} = transfer efficiency, towel-to-mouth (fraction).
CF_{TM} = contact frequency from towel to mouth each day (number of contacts per day).
SA_M = surface area of skin (mouth) (cm^2).
FI_T = fraction ingested from towel contact (fraction).
EF = exposure frequency (days per year).
ED = exposure duration (years).
AT = averaging time (days).
BW = body weight (kg).

In accordance with US EPA (2004) guidance, dose is averaged over a 70-year lifetime (AT) when assessing cancer risk and termed a lifetime average daily dose (LADD), while the AT is set to the same value as the exposure duration (ED) in calculating an average daily dose (ADD) for noncancer hazard assessment. The exposure factor values used in the modeling each of the three exposure pathways are described in Tables 2 and 3, and the cumulative ADD/LADD for all three pathways is presented in Table 4. The basis for these values is described in detail below.

The exposure factor values are average values, which are applicable to multiple contacts throughout a day and numerous contacts across the assumed chronic exposure duration of 25 years (US EPA, 2004). The use of average values is justified in this assessment because of the focus on low-level, but long-term exposures to shop towels.

2.3.4. CF_{TH}, hand to towel contact frequency

The frequency of towel contact by workers is another key component of the exposure model. However, this exposure factor value is likely to be highly variable among workers, being dependent on the nature of towel use and the personal habits of an individual worker. Moreover, if towel number and contact frequency are used as the basis of exposure, the exposures predicted by this model would increase linearly with towel use, i.e., greater hand loading will accompany more frequent towel use. In reality, the opposite is likely to be true: a worker replacing his/her towel more often would be expected to have cleaner hands, since towel use in most instances is aimed at removing dirt and grease from the hands. In addition, studies on pesticide exposures have shown that the pickup by hands from various surfaces is a saturable process, wherein the removal of a residue on the skin eventually becomes as important as the pickup (Brouwer et al., 1999). The maximum load can even be reached within several contacts (Cohen Hubal et al., 2005). The phenomenon of a maximum dermal loading has been incorporated into some of the most advanced dermal exposure models (Zartarian et al., 2000). In an assessment of surface-to-hand transfers in pesticide workers, US EPA (1997) applied a model that did not permit dermal loading to continue beyond the point where the skin concentration exceeded the concentration on the contacted surface.

Therefore, a contact frequency was chosen that is based on the maximum reasonable skin loading that could occur with towel usage. In this manner, skin loading was not allowed to exceed the concentrations on the towels themselves. Where an TE_{HM} of 5% is used to represent the towel-to-hand transfer per contact event, an assumed number of 20 contacts per day will result in a transfer of 100% of the entire available metal content of a towel (per surface area contacted). Thus, a value of 20 contacts per day was chosen as a reasonable maximum for the number of towel contacts in a typical work day. Since the concentration typically found on the hands of workers would probably not equal the concentrations in the towels, this set of assumptions defines a “worst case” scenario.

2.3.5. CF_{HM}, hand-to-mouth contact frequency (number of times worker touches mouth with hands each day)

The number of expected hand-to-mouth contacts is the rate-limiting step in the overall model of worker exposure to towel

Table 2
Exposure factor values.

Variable	Unit	Value	Source	Notes
$TE_{TH/TM}$	Unitless	5%	US EPA (2012); see text	
$TE_{HM/HF}$	Unitless	25%	Cal-EPA (2011); see text	
SA_{HM}, SA_{HF}	cm^2	19; 210	US EPA (2007); see text	
CF_{TH}	Unitless	20	See text	
CF_{HM}, CF_{TM}	Contacts/day	20; 2	Cherrie et al. (2006); see text	
FI_H, FI_T, FI_F	Unitless	50%, 50%, 100%	Professional judgment; see text	
CF_{HF}	Unitless	2	Professional judgment; see text	
SA_M	cm^2	3	Ferrario et al. (2000)	50% of surface area of lips for adult male
EF	Days/year	250	US EPA (2002) default	
ED	Years	25	US EPA (2002) default	
AT	Days	NC: 9,125 Cancer: 25,550	US EPA (1989) default	
BW	kg	70	US EPA (2011) Exposure Factors Handbook	

Notes:
$TE_{TH/TM}$ = skin transfer efficiency, towel-to-hand & towel-to-mouth (fraction).
$TE_{HM/HF}$ = transfer coefficient, hand-to-mouth & hand-to-food (fraction).
SA_{HM}, SA_{HF} = surface area of skin (hand) in contact with mouth or with food (cm^2).
CF_{TH} = towel contact frequency with hands (number of contacts per day).
CF_{HM}, CF_{TM} = face contact frequency (number of contacts between hand and face per day).
FI_H, FI_T, FI_F = fraction of constituent ingested from hand-to-mouth transfer, towel-to-mouth transfer, and hand-to-food transfer.
CF_{HF} = hand-to-food contact frequency (events per day).
SA_M = surface area mouth in contact with towel (cm^2).
EF = exposure frequency (days per year).
ED = exposure duration (years).
AT = averaging time (days).
BW = body weight (kg).
NC = Non-cancer.
U.S. EPA = United States Environmental Protection Agency.
Cal-EPA = California Environmental Protection Agency.
OPP = Office of Pesticide Programs.
OSWER = Office of Solid Waste and Emergency Response.

Table 3
Studies providing an estimate of the skin transfer efficiency.

Reference	Summary values (%)	Matrix	Compound	Skin condition
Cohen Hubal et al. (2005)	2.6	Carpet	Fluorescent-tracers	Dry
Cohen Hubal et al. (2008)	3.6	Carpet	Fluorescent-tracers	Dry
Lu and Fenske (1999)	0.1	Carpet	Pesticides	Dry
Camann et al. (1996)	2.5	Carpet	Pesticides	Dry
Cohen Hubal et al. (2005)	7.2	Carpet	Fluorescent tracers	Moist
Cohen Hubal et al. (2008)	8.7	Carpet	Fluorescent-tracers	Moist
Camann et al. (1996)	0.1	Carpet	Pesticides	Dry
Yang and Li (1993)	1.8	Cotton cloth	Pesticides	Dry/wet/perspiring
Clothier (2000)	5.1	Vinyl flooring	Pesticides	Dry/wet/wetted with Saliva

constituents, assuming that the hands carry a given load from the use of shop towels throughout the day. The review by Cherrie et al. (2006) reported that adults in occupational settings are likely to touch their face approximately 5 times per hour on average, although contacts can increase under stressed situations. Cherrie et al. (2006) also cited the data from Zainudin (2004), to point out that workers who used their hands to perform their jobs, such as manufacturing or laboratory workers, made much lower hand-to-face contact frequencies, as compared with those who did not (e.g., office workers). The highest contact frequencies reported by Zainudin (2004) among these groups was six contacts per hour. A contact frequency of five per hour is also supported by age-dependent behaviors summarized in Xue et al. (2007) (as cited by US EPA, 2011), which focused on children, but found evidence of a rapid decline in contact frequencies with age and that children aged 6–11 years had a mean contact frequency of seven contacts per hour, which was 3 to 4-fold lower than those exhibited by younger children.

Based on these data, a hand-to-face contact frequency for adults of five contacts per hour is reasonable. However, not all hand-to-face contacts will represent a contact between the hands and lips. Nicas and Best (2008) provided one of the only studies of adults which recorded the hand-to-face contacts according to the area of the face contacted. As summarized by US EPA (2011), this study found that roughly 50% of the hand-to-face contacts included the lips or mouth. Therefore, the hand-to-face contact frequency of five contacts per hour (or 40 contacts per day), as estimated by Cherrie et al. (2006), was halved to estimate a hand-to-mouth contact rate of 20 contacts per day.

It is conservatively assumed for this risk assessment that the 20 hand-to-mouth contacts do not start until after the 20 towel-to-hand contacts have occurred. That is, the model assumes 20 towel-to-hand contacts with continuing build-up of metals on the hand with no losses until the metal concentrations on the hand equal the available metal concentrations on the towels. Then the model assumes 20 hand-to-towel contacts, at which time the metals are transferred to the mouth.

2.3.6. C_{towel}, available metal concentrations in towels

The C_{towel} factor is discussed in Section 2.2 above, because this is experimentally determined.

2.3.7. TE_{TH} and TE_{TM}, transfer efficiency, towel-to-hand and towel-to-mouth

With each contact between the hands and a towel or the mouth and a towel, there is an assumed transfer of some fraction of the

Table 4
Average lifetime and daily dose: selected metals.

Constituent	Concentration leachate available (C_{towel}) $\mu g/cm^2$	Exposure model		
		Hand-to-mouth	Hand-to-food	Towel-to-mouth
		ADD (mg/kg-day)		
Aluminum	9.31E − 02	8.62E − 06	1.29E − 05	1.37E − 07
Antimony	2.49E − 02	2.31E − 06	3.44E − 06	3.66E − 08
Arsenic	1.33E − 03	1.23E − 07	1.84E − 07	1.95E − 09
Barium	2.08E − 01	1.93E − 05	2.88E − 05	3.06E − 07
Beryllium	1.24E − 04	1.15E − 08	1.72E − 08	1.82E − 10
Boron	1.22E − 01	1.13E − 05	1.69E − 05	1.79E − 07
Cadmium	2.44E − 01	2.26E − 05	3.38E − 05	3.59E − 07
Chromium	2.73E − 02	2.53E − 06	3.77E − 06	4.01E − 08
Cobalt	4.50E − 02	4.17E − 06	6.22E − 06	6.60E − 08
Copper	8.92E − 01	8.26E − 05	1.23E − 04	1.31E − 06
Iron	5.07E − 01	4.70E − 05	7.01E − 05	7.44E − 07
Lead	5.33E − 03	4.94E − 07	7.37E − 07	7.82E − 09
Magnesium	3.98E + 00	3.61E − 04	5.39E − 04	5.72E − 06
Manganese	1.44E − 01	1.34E − 05	1.99E − 05	2.12E − 07
Mercury	6.50E − 05	6.02E − 09	8.98E − 09	9.54E − 11
Molybdenum	1.01E − 01	9.37E − 06	1.40E − 05	1.48E − 07
Nickel	2.26E − 01	2.10E − 05	3.13E − 05	3.32E − 07
Selenium	1.56E − 03	1.45E − 07	2.16E − 07	2.29E − 09
Silver	7.59E − 06	7.03E − 10	1.05E − 09	1.11E − 11
Strontium	2.44E − 01	2.26E − 05	3.37E − 05	3.58E − 07
Thallium	3.30E − 05	3.06E − 09	4.56E − 09	4.85E − 11
Tin	2.10E − 03	1.94E − 07	2.90E − 07	3.08E − 09
Vanadium	3.25E − 04	3.01E − 08	4.49E − 08	4.77E − 10
Zinc	1.80E + 00	1.66E − 04	2.48E − 04	2.64E − 06
	LADD (mg/kg-day)			
Arsenic	1.33E − 03	4.40E − 08	6.56E − 08	6.96E − 10

Notes:
C_{towel} = loading concentration of metal.
ADD = average daily dose (noncancer).
LADD = lifetime average daily dose (cancer).

metal present on that towel. The skin transfer efficiency (TE) describes the degree to which this transfer will occur. US EPA (2011) provides skin transfer factors (or coefficients) based on several published studies. However, this guidance also recommends that the selection of a transfer efficiency value consider the study data which best represents the conditions of exposure being evaluated, because the transfer of a chemical from a surface depends on the specific conditions of this exposure, such as the nature of the activity, the contract surfaces, and the age of the material. No data are available specifically representing the transfer of metals from fabrics to the hands; however, a number of TE estimates have been published in the literature based on studies measuring the transfer of various chemicals from a variety of consumer products, e.g., garments, carpeting, toys. Many of these studies are focused on pesticides; however, in most cases the contact was with a residue that had been applied to the surface of a material; and therefore, the chemical properties of the substance being studied is not likely the key factor in the observed transfer efficiency. In choosing a TE for this assessment, studies were favored that evaluated the transfer of an *available* concentration of a chemical, such as a chemical that was applied to the surface of a material to be consistent with the data used in this assessment, which represent the dislodgeable concentrations of each metal.

Based on a review of the literature values, US EPA (2012) recommends a default TE value of 6–8% for contact with various surfaces, although the values at the lower end of this range are adequately conservative for representing transfers from soft surfaces. As part of a risk assessment of perfluorooctanoate exposures in garments and apparel, Washburn et al. (2005) chose to use a value of 5% for infants and 2.5% for adolescents and adults following an extensive review of the transfer factors for various materials with soft surfaces, such as carpet or fabric. Each of these values was based on the observed transfer of chemical constituents from clothing to skin. A summary of the various skin transfer efficiencies is presented in Table 3.

Additional studies reviewed include Cohen Hubal et al. (2005) who observed an average TE of 2.4% and 7.2% based on dry and moist hand trials, respectively, using an organic fluorescent tracer compound. In a follow-up study, Cohen Hubal et al. (2008) included a fat-soluble tracer, as well as a water-soluble tracer. For the dry hand condition, the STE estimate from this study was 3.6% and, for the moist hand conditions, 8.7%. These results were heavily influenced by three high values (>10%) from the trials using the fat-soluble tracer. The data for the water-soluble tracer are more representative of the transfer of metals, but all data from this study were included in the assessment.

Lu and Fenske (1999) evaluated the transfer of the pesticide chlorpyrifos from carpeting based on removal by human skin, cloth wipes, and polyurethane foam rollers. According to the study, skin removed between 0.04% and 0.26% of the chlorpyrifos from carpeting for an average TE of 0.13%. Despite using a similar experimental design, Lu and Fenske (1999) reported much lower transfer coefficients than Cohen Hubal et al. (2005, 2008) likely because they measured aggregate transfers after 10 or 50 hand contacts (and dividing by the total area contacted by the hands throughout these contacts). In contrast, Cohen Hubal and coworkers measured the transfer of chemical after each contact (by either hand press or smudge). The differences between the results are likely because transfer rates decline with each hand contact as the hand surface becomes saturated. Therefore, the most reasonable TE value for use in the shop towel model would lie between the values provided by these two study groups.

Camann et al. (1996) developed TE estimates based on the transfer of pesticides from carpet to saliva-moistened hands resulting in an average TE of 2.5%. Additionally, this study reported data from a previous study representing the same tests conducted with dry hands in which the mean transfer efficiency was 0.1%.

Yang and Li (1993) measured the frictional transfer of three different pesticides from cotton, polyester, and blended fabrics to silk (imitating skin) and observed the highest average transfer to be about 6% (averaged for dry, water-wetted, and perspiration-wetted fabrics). Looking only at cotton fabric, the average transfer efficiency for the three pesticides was 1.8%.

Clothier (2000) evaluated the transfer efficiency of pesticides from vinyl flooring to dry and wetted palms and reported a TE of 5.1%. However, this TE represented the use of a smooth surface rather than a textured surface such as a towel, which could result in a higher TE than is applicable to this study.

Based on the review of studies summarized in Table 3 and an emphasis on the values that best represent the transfer of a metal from the towel surface to the skin, 5% was used as the TE for this assessment. This value represents the fractional transfer of the available concentration of each from the towel surface to the skin of the hands over a specified surface area. It is noted that the same transfer efficiency value is applied to direct towel-to-mouth exposures, where it assumed that the towel contacts the skin of the lips.

2.3.8. TE_{HM}, transfer efficiency, hand-to-mouth

Typical contact between the hands and mouth would not result in the transfer of 100% of a chemical constituent that is present on the hands. In fact, even with the most rigorous conditions of dermal contact, a transfer coefficient (TE_{HM}) of more than 50% is difficult to conceive, at which point the concentration of the transferred substance on the lips would exceed that of the hands. Transfer coefficients (TE_{HM}) of 50% have been used in risk assessments evaluating lead exposure via dermal contact (Cal-EPA, 2011; CPSC, 1997), referencing the transfer studies of Camann et al. (2000) and models that simulated the conditions of mouthing behavior in children. The TE_{HM} representing the much more incidental nature of hand-to-mouth contacts in adults is likely to be much less than 50%. A TE_{HM} value of 25% is used as the default choice in US EPA pesticide assessments, and an US EPA (2007) Region 3 assessment addressing dermal exposures to indoor surfaces used a value of 10%. Based on the lack of relevant data characterizing the hand-to-mouth transfers for adults, a value of 25%, which is an intermediate choice among the TE_{HM} values used by others for this same purpose, was used in the risk assessment. The value of 25% also represents the value of 50% developed for young children, adjusted by a factor of 2, which is a very minimal adjustment based on the substantial differences between children and adults with respect to hand-to-mouth contact.

2.3.9. SA_{HM}, surface area fingertips in contact with mouth

Risk evaluations conducted by regulatory agencies for these types of exposures commonly use the surface area that makes contact with the article (Cal-EPA, 2008, 2011; CPSC, 1997, 2010; Washburn et al., 2005). As much as one-third to one-half of the total surface area for both hands is typically assumed to make contact with a surface, which is 180–270 cm^2 for adults (US EPA, 2011). However, where dermal absorption itself is a *de minimis* exposure, the transfer model can focus on the surface area that is likely to make contact with the mouth.

In a recent interpretive guideline for exposure assessments under California's Proposition 65 (Cal-EPA, 2011), the recommended surface area for direct hand-to-mouth contact is that of the palmar surface area of a hand, counting each finger as 10% of the palmar surface area of the hand and counting each fingertip as 30% of the finger. It is further assumed that the part of a hand that is in contact with the mouth is three fingertips (i.e., the tip of a thumb and two fingertips). The resulting values are 19 cm^2 for men and 17 cm^2 for women. The higher value of 19 cm^2 is chosen to represent the surface area of the hands that is assumed to contact the mouth. It is noted that this value is equivalent to about 3 times the surface area of the lips (see below).

2.3.10. FI_H and FI_T, fraction of contacted metal ingested

Subsequent to the transfer of a chemical constituent residue to the lips, some amount of incidental ingestion is typically assumed to occur. The amount of a material applied to the lips that is actually ingested has received recent attention as part of assessments for lipsticks and the trace levels of lead found in lipsticks (Hepp et al., 2009; Cal, 2008). These assessments have concluded that, while there are no data quantifying the exact amount of lipstick (or similar product) that is ingested by users, this amount is likely to be small. Nonetheless, it was assumed for the purpose of this assessment that 50% of the metal transferred to the lips will be ingested. This FI factor is used for the towel-hand-mouth exposure scenario (FI_H) and the towel-mouth exposure scenario (FI_T).

2.3.11. TE_{HF}, transfer efficiency, hand-to-food

In the assessment of indirect contacts that accompany the hand-to-mouth exposure pathway, Cal-EPA (2011) assumed a transfer factor of 25%, attributable to a 50% hand-to-food transfer and a loss fraction of 50% of the skin load that remains on the hands. The loss fraction accounted for the removal of a substance from the hands presumed to occur outside of contact with the mouth, including the handling of foods. The same hand-to-food transfer efficiency of 25% is used in this assessment.

2.3.12. CF_{HF}, contact frequency, hand-to-food

Hand-to-food transfers will occur when a worker who has not washed his or her hands will eat food items such as a sandwich, crackers, or raw vegetables, which are eaten with the hands. While some finger foods, such as chips will involve multiple contacts, the degree of contact made with these foods is also very small, as compared to larger items. Therefore, given that each contact "event" is assumed to involve a substantial surface area (including the palmar surface of the hands), it is assumed that 2 contact events will occur per day on average. It is noted that a contact event must involve a food item eaten with the hands, where the handled part of the food is consumed. It also assumes no amount of loss from hand-washing, which would likely occur before a meal in a shop setting. It is conservatively assumed that these two food contact events occur after workers have contacted shop towels 20 times earlier in the day. Specifically, it is assumed that one contact occurs immediately after the 20 shop towel contacts. The second is assumed to occur mid-way through the period during which the assumed 20 hand-to-mouth contacts occur.

2.3.13. SA_{HF}, surface area hands in contact with food

The surface area of the hands that may come into contact with food is assumed to be 210 cm^2. A conservative model was evaluated assuming that the palmar surface of all ten fingers might come into contact with food. This value was derived from an assessment by Cal-EPA (2008, 2011), wherein each finger was assumed to comprise 10% of the palmar surface of the hand. Conservatively assuming that all ten digits can will make contact with food during a meal, the surface area of all ten fingers will be equivalent to 50% of the surface area of both hands (420 cm^2), or 210 cm^2.

2.3.14. FI_F, fraction ingested from food

It is assumed that 100% of the metals transferred to food from the hands will be ingested.

2.3.15. CF_{TM}, towel-to- mouth contact frequency

The frequency with which an adult worker might bring a towel to his lips was estimated to be 2 times per day. This is in part based on the assumption that towel-to-face contacts, if these contacts do occur, would likely involve other parts of the face. The previous discussion that led to a hand-to-face contact rate of 20 times per day was also considered as a reasonable starting point. However, the nature of the towel-to-face contacts may be quite different than hand-to-face contacts, because they are likely aimed at wiping sweat from a forehead. While there are no good data on the use of shop towels for wiping the face, it is unlikely that an adult worker would use a shop towel for the purpose of wiping his or her mouth. It is therefore assumed that 10% of the hand-to-face contacts would include the lips. Thus, an average contact frequency is assumed to be 2 per day for this assessment. Accordingly, the CF_{TM} is 2 per day. It is conservatively assumed that the contact of towels with the mouth occur in addition to the hand-to-mouth transfers.

2.3.16. SA_M, surface area mouth in contact with towel

The relevant SA for evaluating towel-to-mouth contact is that of the lips, which has been estimated to be 6 cm^2 for adult males (Ferrario et al., 2000). The surface area of the lips in contact with the towel is regarded as the limiting factor in the transfer of towel-based constituents which might ultimately be ingested. It is likely that only half the surface area of the lips would come into contact with the towel. Therefore, a value of 3 cm^2 is used to represent the surface area of the lips that comes into contact with a shop towel.

2.3.17. Other exposure factor values (EF, ED, AT, and BW)

Several other exposure factor values used to quantify exposure (as dose) are based on default values commonly recommended by US EPA, including exposure frequency (EF), exposure duration (ED), averaging time (AT), and body weight (BW). These values and the source of these values are summarized in Table 2. Exposure duration is chosen to represent job tenure for workers and a default value recommended by US EPA (2002) of 25 years is chosen conservatively for this assessment. It is noted that this is a 95th percentile value representing for job tenure in the manufacturing sector for men. US EPA (2011) states that the 25-year default value is likely to be protective of workers "across a wide spectrum of industrial and commercial sectors."

3. Blood lead model

The hazard assessment of lead exposures was based on the conventional approach using blood lead levels as the dose metric for assessing risk. This assessment utilized the US EPA (2003b) Adult Lead Model (ALM), which is based on a biokinetic slope factor of 0.4 μg/dL per μg/day, relating a daily lead intake to a predicted blood lead levels. ALM was used with embedded defaults, except that an exposure frequency for workers was input as 250 days per year and the default bioavailability factor of 12% was changed to 20%. This value reflects the gastrointestinal absorption of soluble lead, rather than an oral bioavailability of lead in soil, which is typically represented by an adjustment of 60% to reflect soil matrix effects.

4. Toxicity values

Toxicity reference values were obtained from authoritative sources, such as US EPA, or the ATSDR, and selected based on the recommended hierarchy presented in *Human Health Toxicity Values in Superfund Risk Assessments* (US EPA, 2003a). The US EPA Integrated Risk Information System is used as the primary source for toxicity values, which are reference doses (RfDs) for the assessment of noncancer hazards and cancer slope factors (CSFs) for cancer risk assessment. The US EPA Office of Solid Waste and Emergency Response (OSWER) Provisional Peer-Reviewed Toxicity Values and the ATSDR Minimal Risk Levels were used as a second tier of toxicity values. Third tier values include RfDs from U.S. EPA's Health Effects Summary Tables. The selected toxicity values are presented in Table 5. For lead, the ALM was used to assess risk. US EPA (2003b) policy uses a blood lead level target of 10 μg/dL, but this assessment used both 10 μg/dL and 5 μg/dL as blood lead targets because the Centers for Disease Control have recommended that the blood lead level target be changed to 5 μg/dL.

5. Risk calculations

The exposure estimates from the model of worker exposure are used with the toxicity reference values to estimate risk, as either a noncancer Hazard Index (HI) or an excess lifetime cancer risk (ELCR) for arsenic, which is regulated as a potential human carcinogen. The HI represents a simple comparison of the exposure estimate (as dose) divided by the RfD (or analogous toxicity value) for each metal, where an HI of less than unity (1.0) indicates that doses are below levels of regulatory concern. The ELCR is estimated as dose multiplied by the CSF. ELCR estimates are compared to regulatory levels of concern, in this case, 1×10^{-6} (one in one million) to 1×10^{-4} (one in ten thousand).

6. Results

Summary statistics for the 27 metals evaluated are presented in Table 1 and include the detection frequency, minimum and maximum detected concentrations, mean and standard deviation, and 95% UCL (on the mean) concentration. The mean and 95% UCL concentrations were calculated using the US EPA Pro-UCL software (v4.00.05) and using a substitution equal to one-half of the detection limit for samples/analytes with undetectable results. As shown in Table 1, the majority of metals evaluated were detected in all 10 samples. Beryllium, boron, silver, thallium, titanium and vanadium were detected in five to nine of the 10 samples, whereas mercury was detected in just two samples, and selenium was detected in one of the 10 samples analyzed. A reference sample, which was comprised of new, unlaundered towels, was also found to contain measureable levels of aluminum, antimony, arsenic, barium, boron, cadmium, calcium, cobalt, copper, iron, lead, magnesium, manganese, molybdenum, nickel, potassium, strontium, tin titanium, and zinc. For arsenic, magnesium, potassium, strontium, and titanium, the concentrations in the reference sample were not different from those in the laundered ("in-use") towels, although it was more common for the laundered towels to have much higher (as much as 100-fold) concentrations of the metals than the reference sample (Table 1).

6.1. Noncancer hazard assessment

The assessment of noncancer hazards was judged on the basis of a Hazard Index (HI, as ADD/RfD) and HIs for 22 metals are summarized in Table 6. Metals that are essential minerals or for which no toxicity criteria exist were not carried through the risk assessment, including calcium, magnesium, potassium, and titanium. Lead was evaluated separately using the US EPA ALM. Hazard indices were calculated for each of the three exposure pathways and for the summed dose resulting from all three exposure pathways. The HI values for the 22 metals were below 1, ranging from 4×10^{-7} to 0.06. The highest HIs were those for cadmium

Table 5
Toxicity values: selected metals.

Constituent	US EPA RSLs			ATSDR MRLs		Critical effect	Notes
	CSF	RfD$_o$ mg/kg-day	Key	Oral MRL mg/kg-day	Duration		
Aluminum		1	P	1	Chronic	Neurological effects	
Antimony		$4.00E-04$	I			Longevity, blood glucose, and cholesterol	
Arsenic	1.5	$3.00E-04$	I	$3.00E-04$	Chronic	Hyperpigmentation, keratosis and possible vascular complications	
Barium		0.2	I	0.2	Chronic	Nephropathy	
Beryllium		$2.00E-03$	I	$2.00E-03$	Chronic	Small intestinal lesions	
Boron		0.2	I	0.2	Intermediate	Decreased fetal weight (developmental)	
Cadmium		$1.00E-03$	I	$1.00E-04$	Chronic	Significant proteinuria	Diet
Chromium		1.5	I			No effects observed	Chromium III
Cobalt		$3.00E-04$	P	$1.00E-02$	Intermediate	Thyroid toxicity and polycythemia	
Copper		$4.00E-02$	H	$1.00E-02$	Intermediate	Gastrointestinal effects	
Iron		0.7	P			Gastrointestinal effects	
Manganese		0.14	I			CNS effects	Diet
Mercury		$1.00E-04$	I			Hand tremor, increases in memory disturbance; objective evidence of autonomic dysfunction	Methyl
Molybdenum		$5.00E-03$	I			Increased uric acid levels	
Nickel		$2.00E-02$	I			Decreased body and organ weights	Soluble
Selenium		$5.00E-03$	I	$5.00E-03$	Chronic	Clinical selenosis	
Silver		$5.00E-03$	I			Argyria	
Strontium		0.6	I	2	Intermediate	Rachitic bone	
Thallium		$1.00E-05$	X			Hair follicle atrophy	Soluble
Tin		0.6	H	$3.00E-02$	Chronic	Hematological effects	
Vanadium		$5.00E-03$	S	$1.00E-03$	Chronic	Kidney effects	
Zinc		0.3	I	0.3	Chronic	Decreases in erythrocyte Cu, Zn-superoxide dismutase (ESOD) activity in healthy adult male and female volunteers	

Notes:
US EPA = United States Environmental Protection Agency.
RSL = regional screening level.
CSF = cancer slope factor.
RfD$_o$ = reference dose, oral.
ATSDR = Agency for Toxic Substances and Disease Registry.
MRL = minimal risk level.
Key: I = IRIS; P = PPRTV; X = PPRTV Appendix; H = HEAST; S = derived from vanadium pentoxide.

(HI = 0.06) and cobalt (HI = 0.04), and the HIs for all metals were at least ten times lower than 1. Each HI is based on the protection of the most sensitive toxicological endpoint, termed the critical effect, or endpoint. For metals that share a common critical effect, the HI values were summed to assess the cumulative hazard associated with simultaneous exposure to these metals. The assessment of cumulative risk is more important as the estimated exposure levels start approaching actual effect levels. The highest endpoint-specific HI was 0.06 for kidney effects. This value is more than ten times lower than the regulatory level of concern.

6.2. Cancer risk

Among the metals evaluated, only arsenic is regulated as a potential human carcinogen by the ingestion pathway and is commonly assessed on the basis of cancer as the endpoint. The US EPA considers cancer risks to be acceptable when in the range of 1×10^{-6} to 1×10^{-4}. The total excess lifetime cancer risk estimated for arsenic and all three exposure pathways was 2×10^{-7}, which is below the lower bound of the range of risk considered acceptable by the US EPA (Table 6).

6.3. Adult Lead Model

US EPA ALM uses a biokinetic slope factor relating blood lead level to ingested lead and data on the background exposures and blood lead levels for the general population. Using this model, lead risk is expressed as a probability that the blood lead levels among a receptor population will exceed 10 μg/dL. US EPA (2003b) considers a probability of 5% as the point of departure for assessing lead risks, which is consistent with a level of protection at the 95th percentile of exposure and risk.

An estimate of the daily lead dose (0.001 μg/kg-day) (Table 4) was calculated with the same exposure model used for other metals and was the starting point for the ALM. Based on this lead dose, the ALM predicts a 0.002% probability of exceeding the 10 μg/dL blood lead threshold and a 0.2% probability of exceeding 5 μg/dL, indicating a *de minimis* risk for lead-related effects. The average estimated lead intake, as estimated in this assessment, would cause no measurable change in blood lead levels. Based on the results of the ALM modeling, predicted changes in blood lead to female workers of child-bearing age who are using the shop towels do not exceed US EPA's target (*de minimis*) risk levels.

7. Discussion

The analysis of shop towels from ten laundering facilities, which formed the basis for this assessment, confirmed previous reports (Beyer et al., 2014) of low, but measurable levels, i.e., part-per-million concentrations, of several heavy metals in reusable shop towels. These trace residues of metals have likely existed for decades and have not prompted concern about worker health. To our knowledge, there have been no reported adverse effects associated with the use of laundered shop towels. While this record of safe human use provides valuable context to the question of any potential health effects associated with shop towel use, the concerns raised by the Beyer et al. (2014) publication merited investigation. In addition, this exposure scenario provides an interesting methodological case study for the assessment of risks from garment/fabric residues.

The assessment of risks in this study is associated with uncertainties as is true with all risk assessments. Uncertainties affecting this assessment are most notably those related to the modeling of worker behavior, towel usage, and the transfer of metal residues from towels to the hands of workers and from the hands to the mouth. The governmental toxicity values used to predict human risks are uncertain, but their derivation addresses uncertainty in a manner that intentionally overestimates risk to humans. The uncertainties related to the exposure assessment are typically the focus of an uncertainty analysis, because the choice of each exposure factor value from within a range of possible values is made at the discretion of the risk assessor. In the case of shop towel use by workers, the primary uncertainties arise from limitations in the data describing the conditions of shop towel use and also by limitations in the current "state of the science" with respect to the transfer of metal residues from shop towels to the worker's hands.

A quantitative uncertainty analysis is not permitted by the available data characterizing the frequency distributions for each exposure factor value, which would account for plausible values at both ends of these distributions. Further, an uncertainty analysis aimed at characterizing the range of available values would not address uncertainties that are likely to be more significant to the overall conclusions, such as the amount of metal residue that undergoes a "reverse transfer" from the hands to the towels, or is otherwise removed throughout the usage period, by touching work surfaces or hand-washing.

In addition, it is important to recognize that the exposure assessment in this paper used an approach common to most health risk assessments, which is to choose reasonable, but high-end values for all exposure factor values. This approach is consistent with the objectives of risk assessment, which is to examine the potential health effects associated with a reasonable maximum, but plausible level of exposure.

Recognizing that the exposure factor values represent likely, average conditions, but are chosen so as not to underestimate the actual exposures to workers, the strength of the data supporting each parameter value is evaluated further below, with a focus on the level of confidence in each choice as a conservative, upper-bound value. The exposure factor values included in this analysis are based on the degree of uncertainty that each is likely to bring to the risk assessment, as identified by our initial development of these values (above) and include: the towel-to-hand transfer efficiency, the hand-to-mouth transfer efficiency, and the face contact frequency.

As a final note regarding the overall uncertainty in the exposure estimates, it is important to note the use of certain limiting assumptions that also increase our confidence in the most tenuous of the assumptions, such as the metal transfer from a towel to the hands. For example, the number of contacts that a worker makes with a towel and then their mouth on a daily basis is a highly uncertain and variable parameter. Rather than making a conservative assumption about the number of contacts, which might poorly represent the majority of workers, this factor was set at a limit of 20, based on a consideration of the resulting net transfer that this would equal. Specifically, the surface of the hands is unlikely to accumulate a metal concentration that exceeds the concentration on the towel itself. Combined with the use of a towel-to-hand transfer efficiency of 5%, the use of 20 contacts per day is in effect, assuming that 100% of the available metal content is transferred each day. Applying this limit to the total transfer is justified based on several studies in the literature measuring the skin pickup of chemicals on soft surfaces, such as clothing (Yang and Li, 1993; Snodgrass, 1992; Camann et al., 1996; Brouwer et al., 1999; Lu and Fenske, 1999; Cohen Hubal et al., 2005, 2008).

7.1. TE_{TH} and TE_{TM}, transfer efficiency, towel-to-hand and towel-to-mouth

The TE of 5% is an important factor in the model of towel-to-hand contact. The confidence in this value is high because of the large number of studies evaluating this factor and the use of similar values by regulatory agencies, which characterize them as conservative. As shown in Table 3, transfer efficiencies substantially less than 5% have been observed in the majority of studies evaluating the transfer of chemicals from soft surfaces like clothing or carpet, and transfer efficiencies as low as 0.1% have been reported. Therefore, this value (5%) is likely to overestimate the actual transfer efficiency.

Transfer efficiencies as high as 13% were reported by Cohen Hubal et al. (2005, 2008) for individual trials representing a particular set of experimental conditions and a single contact event. Such individual estimates are not relevant to the risk assessment, even

Table 6
Hazard indices and cancer risk: selected metals.

Constituent	Kidney	Gastrointestinal	Thyroid	Develop/neuro	Blood	Other	Cancer risk
Aluminum				2.E – 05			
Antimony					1.E – 02		
Arsenic						1.E – 03	2.E – 07
Barium	2.E – 04						
Beryllium		1.E – 05					
Boron				1.E – 04			
Cadmium	6.E – 02						
Chromium						4.E – 06	
Cobalt			3.5.E – 02				
Copper		5.E – 03					
Iron		2.E – 04					
Manganese				2.E – 04			
Mercury				2.E – 04			
Molybdenum	5.E – 03						
Nickel						3.E – 03	
Selenium		7.E – 05					
Silver						4.E – 07	
Strontium						9.E – 05	
Thallium						8.E – 04	
Tin					8.E – 07		
Vanadium	2.E – 05						
Zinc						1.E – 03	
TOTAL	6.E – 02	5.E – 03	3.E – 02	6.E – 04	1.E – 02	6.E – 03	2.E – 07

as upper-bound estimates of exposures. All measures of transfer efficiency representing multiple contacts were much lower, with a maximum value of 7%.

Lastly, it is noted that the importance of this exposure factor value is diminished by its use in conjunction with a contact frequency of 20 events per day, wherein a total daily transfer of 100% of the available metals in the towels is assumed to be transferred to the hands.

7.2. Hand-to-mouth transfer coefficient

The review of the available literature supports an assumed hand-to-mouth transfer efficiency of 25% based on the typical nature of hand-to-mouth contacts in adults. Higher values have been used; for example, in an assessment of dermal exposure to lead-bearing fishing tackle, Cal-EPA (2008) used a value of 50% based on the study of Camann et al. (2000), but also citing CPSC (1997) and US EPA (2011). However, values much lower than 50% have also been used to represent the TC_{HM} for adults. Dubé et al. (2004) proposed a TC_{HM} value for adults of 13% as the fraction of a single hand loading necessary to equal the average daily soil ingestion rate for adults. Thus, the value of 25% used in this assessment is supported by a body of research examining hand-to-mouth transfers and the uncertainty in this value is modest, with a range of possible values described by a factor of about 2×. The value of 25% is a conservative, high end value when it is considered that a large percentage of hand-to-mouth contacts will likely achieve a transfer of chemical constituent residues that is minimal or even negligible.

7.3. Face contact frequency

Of the exposure pathways evaluated in this assessment, hand-to-mouth transfers are the most difficult to model, because contact frequency is highly variable among individuals. Cherrie et al. (2006) recognized that there are no suitable methods available to measure the potential for ingestion exposure where the underlying processes are unintentional. While there is a large body of work documenting the role of hand- and object-to-mouth contact in children, there are limited data in adults. Many of these studies note a decrease in mouthing behaviors with age, although there is a substantial variation in behaviors (Tulve et al., 2002 as cited in Cherrie et al., 2006). The available studies examining adult behavior do indicate that adults touch their face much less often than children. A study of 44 university students found that adults touched their face an average of 3.9 times per hour and mouthed objects 1.6 times per hour (Woods and Miltenberger, 1996 as cited in Cherrie et al., 2006). Zainudin (2004) hypothesized that those engaged in work requiring the use of their hands were less likely to touch their face.

The decision to apply a conservative hand-to-mouth contact rate of five times per hour is based on the available research for adults and common use of this value in other exposure models (Cherrie et al., 2006).

According to the US EPA (2011) *Exposure Factors Handbook*, 10–12 year olds can be expected to mouth objects once an hour on average and display hand-to-mouth contacts four times per hour. These findings are consistent with the value of 20 hand-to-mouth contacts per day (2.5 contacts per hour) used in this assessment, which is focused on adult workers.

The stated variability in this exposure factor value could prompt the use of a more conservative, higher-end value. However, each of the 20 transfer events is assumed to represent a full contact event, that is, each contact is assumed to transfer the entire amount, in accordance with the transfer coefficient of 25%. Further, some skin transfer factors that are intended for the cumulative exposure over the course of a day are in the same range, indicating that the 25%, as discussed previously is a very conservative assumption.

7.4. Toxicity assessment

The metal with the highest HI of the metals evaluated was cobalt. In the absence of a US EPA RfD for cobalt, this assessment used the US EPA provisional RfD (p-RfD) of 3×10^{-4} mg/kg-day. USEPA derived this p-RfD based on changes in iodine uptake in the thyroid, a Lowest Observed Adverse Effect Level (LOAEL) of 1 mg/kg-day, and a combined uncertainty factor (UF) of 3000 (10 for the use of subchronic data, as noted, plus 10 for the use of a LOAEL, 10 for potential human variability, and 3 for the deficiencies in the available data characterizing cobalt toxicology.) Provisional toxicity values do not receive the same level of peer-review as more formally established toxicity values from US EPA and often contain a higher level of conservatism by comparison. Therefore, the toxicity values for cobalt derived by others should be considered. Finley et al. (2012) proposed a chronic RfD for cobalt using standard U.S.EPA methods and derived based on iodine uptake (by thyroid) in children. This alternative RfD of 0.03 mg/kg-day was based on a point of departure (POD) of 0.9 mg/kg-day based on a chronic study. However, these authors used an aggregate UF of 30, because there was no need for UFs based on use of a LOAEL and use of subchronic data. The ATSDR Minimum Risk Level of 0.01 mg/kg-day for intermediate-duration exposures is based on a LOAEL of 1 mg cobalt/kg-day for polycythemia observed in a study with humans and an aggregate uncertainty factor of 100. Polycythemia, measured as an increase in erythrocyte (red blood cell) counts, has been very well characterized in animal studies as well as studies in human volunteers, with doses of 0.16–1.0 mg cobalt/kg/day eliciting effects in humans, consistent with the LOAELs observed in animal studies.

7.5. Approach to exposure modeling

The approach applied to the modeling of worker exposure is another methodological choice that affects the overall uncertainties in this risk assessment and explains the very different conclusions of this assessment as compared to those of Beyer et al. (2014). The approach used to model worker exposure by Beyer et al. (2014) was necessitated by the data collected by these authors, which were in the form of bulk concentrations (as percent of towel mass by weight) for each metal using a method that totally dissolved the towel samples in strong acids, thus solubilizing all metals regardless of their bioavailability. In contrast, this assessment collected and utilized data representing the available (dislodgeable) concentrations of each metal in the towels, measured with a leachability test protocol. Thus, a transferable mass of each metal in the towels serves as a starting point for this assessment. This eliminates a significant source of uncertainty in the Beyer et al. (2014) assessment, namely, that related to estimating the fraction of the bulk concentration that is available for contact with, and transferable to the hands of the user. In the face of the uncertainty associated with this factor, Beyer et al. (2014) assumed that 100% of the bulk concentration is available, or dislodgeable, despite their own data indicating that much of the metal content is bound in the towels as solids and unavailable. Examination of laundered towels using electron microscopy (Beyer et al., 2014) found that the metal content of the towels is associated with distinct particles embedded within the fabric. As such, a leachability test protocol, as used in this paper, captures the metal content of the towels more efficiently than a bulk testing.

8. Sensitivity Analysis

As discussed above, a quantitative uncertainty analysis of this risk assessment is not supported by the available data. However, a brief discussion of the intrinsic uncertainties influencing the exposure factor values is still warranted because, in some instances, these choices are based on professional judgment. A brief sensitivity analysis is conducted to examine which factors are making the largest contribution to uncertainty. The results are intended to assist future efforts to better understand the nature of these types of exposures. Each of the exposure factors and the basis for choosing a single value to represent each was addressed in depth throughout this paper. The exposure factor values can be ranked as follows, with respect to their contribution to the overall uncertainty in this assessment.

The expected range of uncertainties embodied by each exposure factor value used in this assessment
Exposure factor values with low uncertainty (<20%)
C_{towel}, SA_{HM}, SA_{M}, AT, BW
Exposure factor values with moderate uncertainty (<50%)
EF, ED, FI_{H}, FI_{T}, FI_{F}
Exposure factor values with high uncertainty (>50%)
TE_{TH}, CF_{TH}, CF_{HM}, CF_{TM}, CF_{HF}

The factors with the lowest amount of uncertainty are those that are actually measured, such as the concentration of metals in the towels and the surface areas of the hands or lips. The uncertainty inherent in these values is based on measurement error or natural variation in a population, but none are significant compared to the overall uncertainties in risk assessment. The next category includes some factors very common to all risk assessments, such as exposure frequency and exposure duration. This assessment used the default values for these exposure factor values, which are commonly chosen at the high-end (e.g., 95th percentile value). The use of such conservative default values is well entrenched in the practice of risk assessment, but it is notable that these values overstate the values applicable to the average worker by as much as a factor of twofold. The FI term, which represents the fraction of a substance transferred to the lip area which is actually ingested, is also in this category. In this case, the data are adequate to support the value of 50%, although it is likely that, on average, this value will actually be much lower (as low as 10%). It is noted that Beyer et al. (2014) incorporated this factor into the term representing hand-to-mouth transfer efficiency (HTE). However, a comparison is possible by combining the FI term (50%) with the transfer efficiency (25%) used in this assessment. The combined value is 12.5%, which is still about two times higher (more conservative) than the HTE of 6% used by Beyer et al. (2014).

The final category of exposure factors include those making the largest contribution to the overall uncertainty, and these include the exposure factor values for the contact frequencies between the towel and hands (or face) of a worker, and the contact frequencies between the hands with food or the face, and the transfer efficiencies governing the migration of a metal from a contacted surface to the hands (or face). The uncertainty associated with these factors is addressed by choosing values for high-end conditions of exposure. To ensure that these exposure factors are conservatively high, it is important to consider the net transfers that can reasonably be expected to occur over the course of a day. Specifically, the values for transfer efficiency and contact frequency were chosen such that the combination of each defines a net transfer that is at the upper limit that is possible. For example, the towel-to-hand transfer efficiency (TE_{TH}) of 5% when used in conjunction with a contact frequency of 20 uses per day equates to the assumed daily transfer of 100% of the available metal content. This gives much greater confidence in the conservatism in these values, since a transfer of 100% of the metal content of a towel is really not expected, and certainly cannot be exceeded. (In fact, following the transfer of 50%, the hands and towel would theoretically reach an equivalent surface concentration, at which point, reverse transfers from hand to the towel would be just as likely.)

A second factor mitigating the uncertainty in the assumed transfer efficiencies is that the studies cited in this paper have clearly demonstrated that transfer efficiency decreases with the number of contacts between hand and the contacted (surface) material. In fact, some negative transfer can occur after several contacts. Cohen Hubal et al. (2005) found that maximal transfer occurred with only 5–7 contacts. The present exposure model makes an assumption of 20 contacts per day, a value well above the number of contacts where the transfer efficiency is expected to reach a plateau. Therefore, not only is it appropriate to use the transfer efficiencies representing the results from multiple contacts, but the available data are likely to overstate the average transfer efficiencies occurring over numerous daily contacts.

In summary, this discussion of uncertainties confirms that this risk assessment was conducted in a manner that is consistent with its objective, which was to estimate exposures in a manner that overestimates the actual risk.

9. Conclusions

An assessment of heavy metal exposures through the use of shop towels was carried out because of previous reports of residual concentrations in laundered towels. The results indicate that there is no increased health risk above regulatory levels of concern for workers who routinely use shop towels, from a variety of exposure pathways. The exposure model was based on the premise that dermal absorption of metals will be negligible as compared to indirect exposure pathways that lead to the incidental ingestion of the metals. This was confirmed by a brief analysis of the potential dermal absorbed dose using US EPA permeability constants for inorganic metal salts.

A leachate analysis was performed to determine the available concentration of residual metals from a standard shop towel that could be transferred onto the skin of workers. Exposures were quantified with standard US EPA-type models and scientifically-based inputs, focused on towel-to-hand, and towel-to-mouth exposure pathways. The conclusions of this assessment apply to normal, foreseeable towel use and conditions of worker exposure, as described in this risk assessment.

Hazard indices calculated for 26 metals (excluding lead) were below 1, indicating that predicted worker exposures were below levels which would indicate a potential health risk. The incremental cancer risks estimated for metals that are regulated as carcinogens (arsenic only) was 2×10^{-7}, near the lower end of the range of risks considered to be acceptable by US EPA (10^{-6} to 10^{-4}). Additionally, lead risks as evaluated by US EPA ALM were below levels of a significant health concern as evaluated in this assessment. Based on our findings, the residual concentrations of metals in laundered shop towels do not present a health hazard for workers using the towels.

Conflict of interest

None.

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