

Dermal Uptake from Airborne Organics as an Important Route of Human Exposure to E-Waste Combustion Fumes

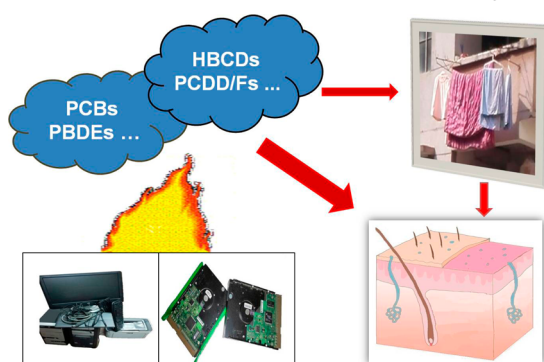
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Skin absorption of gaseous organic contaminants is an important and relevant mechanism in human exposure to such contaminants, but has not been adequately examined. This article demonstrates that dermal uptake from airborne contaminants could be recognized as a significant exposure route for local residents subjecting to combustion fume from e-waste recycling activities. It is particularly true for organic pollutants which have high dermal penetration rates and large skin-air partition coefficients, such as low molecular weight plasticizers and flame retardants.

■ INTRODUCTION

Rapid technological advances and strong consumer demand for innovative products have led to a high obsolescence rate of electrical/electronic devices (commonly called e-waste) worldwide. For example, new cell phone models are released at high frequency.¹ It was estimated that 20–50 million tons of e-waste are generated every year globally,¹ approximately 80% of which is transported cross-boundary to China, India, Vietnam, Ghana, and Russia for recycling and disposal.^{1,2} Due to the lack of adequate preventive measures with recycling and disposal activities, a wide range of chemicals has been found to release into the environment,^{3,4} including methane and other light hydrocarbons, volatile organic compounds such as benzene, and semivolatile organic compounds (SVOCs). Among SVOCs, the commonly occurring compounds include phthalate, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs) and polychlorinated dibenzo-*p*-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF),^{3–7} which are potential carcinogenic and hazardous substances.

Several studies have assessed the relative contributions of inhalation, dietary intake, dust ingestion and dermal absorption to the total concentrations of selected chemicals in residents dwelling in e-waste recycling zones.^{3,8} Previous assessments of dermal exposure have focused on one type of contact transfer, that is, inadvertent touch with contaminated dust or soil,^{3,8} but dermal absorption of both particulate and gaseous contaminants through air-to-skin transport has been largely overlooked.^{9,10} The skin air-mediated exposure, similar to inhalation, occurs constantly. Furthermore, concentrations of urinary metabolites due to dermal uptake from airborne contaminants, such as low molecular weight phthalates and 2-butoxyethanol, were roughly equal to or even greater than those from inhalation exposure.^{11,12} Technically, exposure risks through dietary intake, dust ingestion, and inhalation for local residents or workers can be substantially reduced with proper protective measures, such as avoiding consumption of locally contaminated foods, washing hands before eating and wearing respiratory protection mask. Therefore, human dermal uptake from airborne organic contaminants is deemed significant in inducing health risk for residents dwelling in e-waste recycling zones, but has not been examined adequately.

The aim of this article is to demonstrate that dermal uptake could be a significant route for local residents to expose to combustion fume from e-waste recycling activities. In the rest of this article, we will review the current results about the dermal absorption and its permeation mechanisms, and then assimilate available information about dermal exposure to chemicals via direct air-to-skin transfer and clothing-mediated transport. Finally, we will examine various factors influencing dermal absorption, that is, physicochemical properties, effectiveness of cleaning, “wash-in” effect, and follicular penetration.

■ DERMAL ABSORPTION AND CROSS-SKIN TRANSPORT

As the largest organ of a human body (~15% of body weight),¹³ skin consists of three layers, from outer to inner, *epidermis*, *dermis*, and subcutaneous tissue. The outer of the *epidermis* is called stratum corneum, which is highly hydrophobic and provides protective mechanisms for skin.^{13,14}

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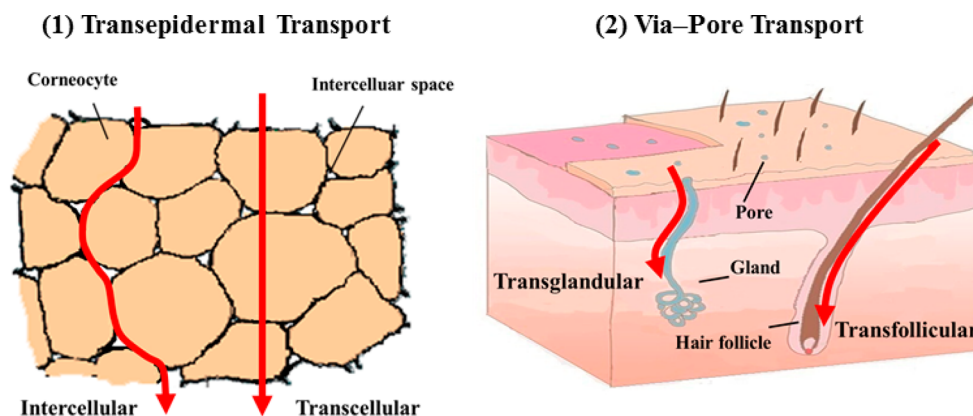


Figure 1. Two pathways for chemicals to permeate the stratum corneum.

Table 1. Concentrations of PCDD/Fs, PBDEs and Other Flame Retardant (pg m^{-3}) in the Atmosphere around E-Waste Areas in China

site			sampling period	mean	range	pg of TEQ $\text{m}^{-3\text{a}}$	ref		
Guiyu	PCDD/Fs	warm period ^b	gas	35	NA ^c	6.65	6		
			particle ^d	93	NA	2.13	6		
		cold period ^b	gas	2.0	NA	0.24	6		
			particle	250	NA	15.8	6		
Guiyu	di-, tri- and tetra-PBDEs ^e	warm period ^b	gas	3700 ^f	NA	NA	5		
			particle	530	NA	NA	5		
		cold period ^b	gas	2100	NA	NA	5		
	particle		8800	NA	NA	5			
	penta- and hex-PBDEs ^g	warm period ^b	gas	940	NA	NA	5		
			particle	1400	NA	NA	5		
cold period ^b		gas	100	NA	NA	5			
	particle	8300	NA	NA	5				
Qingyuan	di-, tri- and tetra-PBDEs ^h	warm period ⁱ	gas	800 ^j	300–1400 ^k	NA	7		
			particle	42	8–79	NA	7		
		cold period ⁱ	gas	250	130–440	NA	7		
			particle	74	22–180	NA	7		
			penta- and hex-PBDEs ^l	warm period ⁱ	gas	67	31–93	NA	7
					particle	260	46–550	NA	7
	cold period ⁱ	gas	11	5–44	NA	7			
		particle	220	100–730	NA	7			
		PBT+ <i>p</i> -TBX+PBEB+HBB ^m	warm period ⁱ	gas	140	79–300	NA	7	
				particle	61	21–160	NA	7	
	cold period ⁱ		gas	22	4–31	NA	7		
		particle	46	16–110	NA	7			

^a2378-TCDD equivalent concentration. ^bWarm period: September 2005; cold period: December 2005. ^cNA: not available. ^dTotal suspended particle. ^eSum of five PBDE congeners (BDE-17, 28, 47, 66, and 71). ^fNot indicated as either a mean or median value in the original literature. ^gSum of six PBDE congeners (BDE-85, 99, 100, 138, 153, and 154). ^hSum of 15 PBDE congeners (BDE-7, 8, 11, 12, 13, 15, 17, 25, 28, 32, 33, 35, 47, 49, and 66). ⁱWarm period: from July to September, 2007 and from April to June, 2008; cold period: from October 2007 to March 2008. ^jMedian value. ^k(A–B) represents the range from A to B. ^lSum of nine PBDE congeners (BDE-99, 100, 116, 119, 138, 153, 154, 155, and 166). ^mpentabromotoluene (PBT), 2,3,5,6-tetrabromo-*p*-xylene (*p*-TBX), pentabromoethylbenzene (PBEB), and hexabromobenzene (HBB).

Beneath *epidermis*, *dermis*, enriched with capillary vessels, is the site of hair follicles, sweat glands, and sebaceous glands. In general, there are two options for substances to permeate the stratum corneum, that is, transepidermal and via-pore transport (Figure 1).¹⁵ Transepidermal transport can occur via transcellular or intercellular route, and the latter is the common route for materials such as drugs to permeate the skin.^{15,16} Via-pore transport can proceed through transglandular or transfollicular route, providing shunt paths through the stratum corneum.¹⁵ Because diffusion is considered as the mechanism for uptake of chemicals through skin layers, the physicochemical characteristics of the skin and physicochemical properties of the

chemicals are the controlling factors governing the chemical mass transfer across the skin.¹⁰ For example, the mass transfer of moderate lipophilic chemicals is resistant in the stratum corneum, whereas viable *epidermis* serves as a rate-limiting step in dermal diffusion of highly lipophilic chemicals.¹⁶

During a 24 h period, a human inhales approximately 36 m^3 air into the lung, but at the same time 260 m^3 of air hit the skin, assuming an adult breathing rate of $1.5 \text{ m}^3 \text{ h}^{-1}$,¹⁷ skin area of 1.8 m^2 ,¹⁷ and mass transfer coefficient for SVOCs between bulk air and human skin surface of approximately 6 m h^{-1} .¹⁰ Apparently, dermal uptake results in much higher exposure to chemicals than inhalation, particularly if they have high dermal

Table 2. Concentrations of Airborne BDE-47 and BDE-99 and Calculated Daily Exposure ($\text{ng kg}^{-1} \text{d}^{-1}$) to BDE-47 and BDE-99 via Air-to-Skin Transport and Inhalation by Adults and 3-Year Old Children in Guiyu, an Electronic Waste Recycling Site in South China

		C_g^b	C_p^b	DI_{ig}^c		DI_{ip}^d		$DI_{ig}+DI_{ip}$		DI_{dg}^e		$\frac{DI_{dg}}{(DI_{dg}+DI_{ig}+DI_{ip})}$	
				adults	children	adults	children	adults	children	adults	children	adults	children
BDE-47	warm period ^a	2365	383	0.47	1.53	0.08	0.25	0.55	1.77	0.65	1.1	0.33	0.21
	cold period ^a	863	5282	0.17	0.56	1.06	3.41	1.23	3.96	0.24	0.4		
BDE-99	warm period	806	850	0.16	0.52	0.17	0.55	0.33	1.07	0.61	1.03	0.33	0.21
	cold period	64	4848	0.01	0.04	0.97	3.13	0.98	3.17	0.05	0.08		

^aWarm period: September 2005; cold period: December 2005. ^b C_g and C_p are the atmospheric concentrations of gaseous and particle-bound BDEs from Chen et al.,⁵ respectively (pg m^{-3}). ^c DI_{ig} : daily inhalation exposure to atmospheric BDE compound. $DI_{ig} = C_g \times \text{InhR} \times \text{ED}$, InhR: the inhalation rate ($\text{m}^3 \text{kg}^{-1} \text{d}^{-1}$); ED: the exposure duration (h d^{-1}). ^d DI_{ip} : daily inhalation exposure to particle-bound BDE compound. $DI_{ip} = C_p \times \text{InhR} \times \text{ED}$. ^e DI_{dg} : daily dermal exposure to atmospheric BDE compound. Equations and all parameters for daily exposure were from Tables 2 and S3 of Little et al.²⁷ and Tables 1 and 3 of Weschler et al.¹⁰ except the value of 24 h were used for ED, k_{p-g} for BDE-99 was derived from the equations from Table 1 of Little et al.²⁷

penetration rates and large skin-air partition coefficients. Numerous studies have demonstrated that dermal exposure to airborne organic chemicals can significantly contribute to dose.^{11,18} For example, Johanson and Boman¹⁸ found that the amount of 2-butoxyethanol by dermal uptake was approximately 75% (with a range of 45–85%) of the total uptake amount (including both inhalation and dermal uptake) upon whole body exposure to 2 h period of 2-butoxyethanol vapor.

Upon 6 h human exposure to diethyl phthalate (DEP) and di(*n*-butyl) phthalate (DnBP) vapor in a chamber,¹¹ the median dermal and inhalation uptakes of DEP directly from air were 4.0 and 3.8 μg ($\mu\text{g m}^{-3}$ in air)⁻¹, respectively, whereas those of DnBP were 3.1 and 3.9 μg ($\mu\text{g m}^{-3}$ in air)⁻¹. Furthermore, the concentrations of DEP and DnBP metabolites in human urine samples from both dermal uptake and inhalation increased quickly, with inhalation inducing slightly greater metabolite concentrations than dermal uptake. These results illustrated the importance of dermal absorption of airborne SVOCs as an exposure pathway; especially for low molecular weight phthalates.

Our recent study¹⁹ indicated that consumer exposure to outdoor barbecue fumes in summer can increase the possibility of dermal uptake as a major route of air-pollutant intake. For example, the total fluxes of PAHs (daily exposure duration was assumed to be 1 h) due to dermal uptake (0.2–50 ng d^{-1} of BaP_{eq}) were comparable to or larger than those via inhalation (2.8–26 ng d^{-1} of BaP_{eq}) and ingestion of charcoal-grilled meat (22–220 ng d^{-1} of BaP_{eq}). Furthermore, the estimated incremental lifetime cancer risk through dermal uptake from gaseous PAHs (with a 95% confidence interval of 1.7×10^{-8} – 9.8×10^{-6}) was greater than that via inhalation of gaseous and particle-bound PAHs (with a 95% confidence interval of 1.2×10^{-8} – 4.8×10^{-6}).

Presumably, dermal uptake would also become a major intake route of airborne pollutants for e-waste recycling workers and/or residents dwelling in e-waste zones with extended exposure to outdoor air pollutants, for example, combustion fumes from e-waste processing. The use of largely primitive recycling methods, for example, opening burning and grilling of electronic components over honeycombed coal fires^{3–5,20} which are similar to outdoor barbecue activities that generate toxic fumes, may also produce a number of highly toxic pollutants during recycling processes. Particularly, concentrations of low molecular weight PBDEs and 2378-TCDD equivalent concentrations of PCDDs were greater in the gaseous phase than in the particle phase during warm periods

around e-waste recycling zones (Table 1). Apparently, low molecular weight PBDEs were more bioavailable than mid to high molecular weight congeners,²¹ and lower brominated PBDEs showed greater toxicological effects than higher brominated congeners.²² Moreover, the concentrations of airborne pollutants around a human body may be lower than, equal to or higher than the ambient air concentrations, which is known as personal cloud effect.²³ For example, the ratio of person to room concentrations of atmospheric PBDEs increased from 0.9–1.6 for gaseous-phase congeners to 2–4 for particulate-bound congeners.²³

In Guiyu, the daily dermal intake of gaseous BDE-47 and BDE-99 through air-mediated transfer by adults at an e-waste recycling site, estimated based on air concentrations and other data from Chen et al.'s study,⁵ were 0.65 and 0.61 $\text{ng kg}^{-1} \text{d}^{-1}$, respectively, during the warm period (September), exceeding those via inhalation of both gaseous and particle-bound BDE-47 (0.55 $\text{ng kg}^{-1} \text{d}^{-1}$) and BDE-99 (0.33 $\text{ng kg}^{-1} \text{d}^{-1}$) (Table 2). In addition, the annual air-mediated transfer of both BDE-47 and BDE-99 was approximately one-third of the total of summer and winter (Table 2). On the other hand, in addition to chemicals with great dermal penetration rates, for example, BDE-47 and PCB-28 with k_{p-g} greater than 0.1 m h^{-1} ,¹⁰ chemicals with small skin-air partition coefficients should also be of concern, particularly those with ample emissions during combustion. For instance, the k_{p-g} for benzene (0.00066 m h^{-1} , which was obtained from Equation S5 and Table S5 of Weschler et al.²⁴) is substantially smaller than that of PCBs ($>0.1 \text{ m h}^{-1}$); however, the amount of benzene emitted from e-waste can be up to 8 orders of magnitude larger than that of PCBs. A previous study estimated that approximately 18–68 $\mu\text{g g}^{-1}$ of benzene were emitted during e-waste combustion, as compared to 0.15–0.26 pg g^{-1} for total PCBs.²⁵ This was also corroborated by the detection of benzene in urinary samples from firefighters postfirefighting.²⁶

These findings indicate that any dermal exposure assessment may not be complete if only inadvertent touch with contaminated dust or soil is considered but without accounting for direct transfer through skin of airborne organics. Clearly additional research is warranted.^{10,27} Thus, dermal uptake from airborne pollutants should be regarded as a significant pathway for human exposure to e-waste combustion fume, particularly for volatile organic pollutants with high dermal penetration rates or with low dermal penetration rates but abundant contents during e-waste combustion.

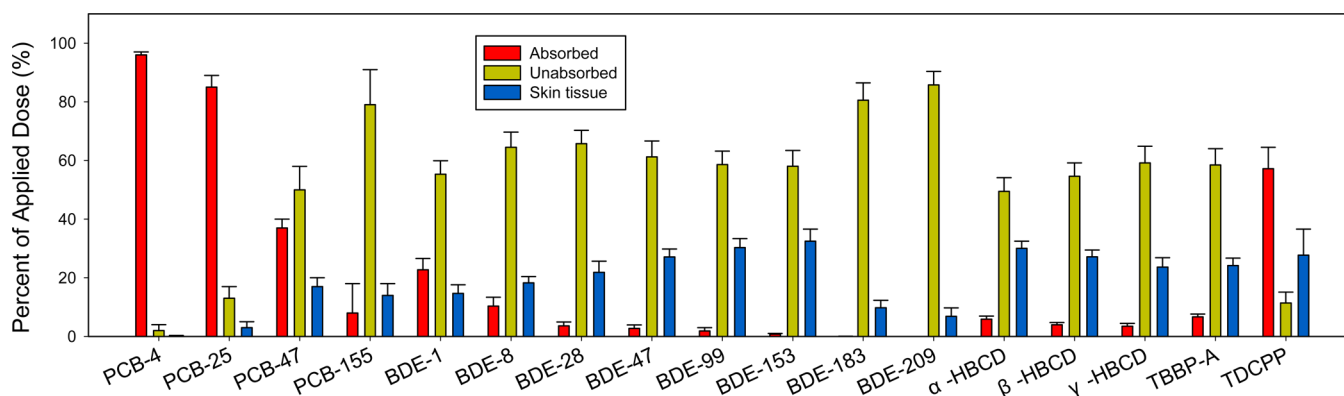


Figure 2. Distributions of flame retardants (expressed as % of exposure dose) absorbed (present in the receptor compartment), unabsorbed (remaining in the donor compartment and on skin surface) and accumulated in the skin tissue of different samples for the in vivo and in vitro dermal absorption studies following 24 h exposure (compiled from Garner and Matthews,⁴³ Hughes et al.,⁴⁵ and Abdallah et al.^{44,46}).

On the other hand, dermal uptake from airborne pollutants has been recognized as a significant input route in occupational exposure.^{26,28} Urinary samples from firefighters postfirefighting contained elevated concentration levels of aromatics (e.g., benzene) and selected PAHs and their metabolites, although self-contained breathing apparatus and protective equipment were used.^{26,28} In addition, higher levels of PBDEs were observed in Southern California firefighters' serum samples, as compared to those from the general population of California during the same period.²⁸ Other epidemiological studies also confirmed that skin related diseases and/or cancer, for example, skin, prostatic and testicular cancer, and non-Hodgkin lymphoma, were associated with firefighting activities among firefighters.²⁹ On the other hand, residents dwelling in e-waste recycling zones are obviously less equipped with protective tools than firefighters. As a result, the potential body burdens of pollutants through dermal uptake from e-waste combustion fume are great in local residents, particularly in warm periods of time. Some examples are Uganda, Peru, Senegal, Kenya, Colombia, Morocco, South Africa, Mexico, and Brazil, besides India and China, which are located in subtropical or tropical areas and employ largely primitive recycling methods.²

DERMAL EXPOSURE VIA FABRICS-MEDIATED TRANSPORT

Dermal uptake of airborne pollutants from air is potentially mediated by clothes. Fabrics are recognized as a possible exposure route, but there have been few studies concerning transport of chemicals to textile materials from air.³⁰ Morrison et al.³¹ recently evaluated the influences of freshly cleaned and pre air-exposed clothes (clean cotton clothes exposed to phthalates for at least 1 week prior to use) on dermal exposure to phthalates, DEP and DnBP, with the clothed participants being exposed to phthalates vapor in a chamber. After 6 h exposure, urine samples of the participants with pre air-exposed clothes contained greater concentrations of DEP and DnBP metabolites than those of the participants with fresh clothes. The results indicated that freshly cleaned clothes were protective, whereas pre air-exposed clothes enhanced dermal uptake of DEP and DnBP by the factors of 3.3 and 6.5, respectively, compared to the average results for bare-skinned participants.³¹ Accordingly, clothes with sorbed pollutants may substantially enhance dermal uptake of SVOCs compared to bare skin, even if the exposure is nonoccupational. In addition, gaseous methamphetamine, a substituted amphetamine and

central nervous system stimulant, was reported to accumulate on cotton and polyester clothes, toy fabrics, upholstery, and skin oil.³⁰ Because fabrics and skin oil have large absorption capacity, the concentrations of methamphetamine accumulated on fabrics and surfaces covered by skin oils might exceed the recommended standards for residential surfaces, even if the air concentrations of methamphetamine were low.³⁰ Therefore, previously exposed clothes may also increase the likelihood of dermal exposure to airborne contaminants,^{32,33} particularly in countries where clothes are often dried under sunlight.

Fabrics are often treated with a wide variety of chemical additives to enhance their utility and may potentially subject human bodies to unexpected chemical exposure. For example, wearing permethrin-treated tick-proof pants may lead to increased body uptake of these substances.³⁴ Faulde et al.³⁵ also reported that untreated fabrics were cross-contaminated during laundering with freshly factory-based permethrin-impregnated battle dress uniforms. Approximately 3–5% to 15–50% of the initial permethrin content of the treated material was transferred to untreated clothes, depending on the composition of fabrics and treated methods used. Cross-contamination during laundering may cause health concerns, even increased risk of disease. In fact, several “para-occupational” diseases occurred in workers' families due to the transfer of hazardous materials from worksites to homes by workers.³⁶ For example, elevated concentrations of PCBs were found in serum and adipose from wives of workers in a railway company, where PCBs had been used as dielectrics.³⁷ Accordingly, laundering contaminated working clothes was suggested as the most common source of cross contamination.³⁷ Thus, dermal exposure through laundering is another important route of human exposure, particularly for residents who hand-wash clothes, which, for example, has remained a popular practice in China.³⁸

As mentioned above, fabrics can accumulate gaseous chemicals. Thus, the possibility for reemission of sorbed pollutants from fabrics is high, causing adverse health effects. Recent studies showed that exposure to smoke fume constituents reemitted from fabrics,³⁹ defined as third-hand smoke, could cause significant genetic damage in human cells.⁴⁰ Faulde et al.³⁵ reported that untreated fabrics were cross-contaminated by permethrin-impregnated uniforms during storage, whether contact was direct or indirect. Park et al.²⁸ also reported lower serum PBDE concentrations in firefighters who cleaned their turnout gear after fire events than those in

firefighters who did not. In addition, clothes containing naphthalene were reported to result in baby death and severe brain damage, due to breakdown of red blood cells in children with a genetic condition called glucose-6-phosphate dehydrogenase (G6PD) deficiency.⁴¹

■ PHYSICOCHEMICAL PROPERTIES INFLUENCING DERMAL ABSORPTION

Skin contamination by PAHs has been found as the main determinant of the internal exposure dose in occupational workers such as chimney sweepers,⁴² as a result of dermal absorption. Dermal exposure to flame retardants has been examined in recent years (Figure 2). For example, Garner and Matthews⁴³ reported the dermal penetration of four ¹⁴C-labeled mono- to hexa-PCBs (¹⁴C-PCB-4, -25, -47, and -155) in adult male F-344 rats was disproportional to the level of chlorination, that is, from ca. 100% for mono-PCB to ca. 30% for hexa-PCB at 48 h. The maximum internal exposure to mono-PCB occurred at 4 h with ca. 40% of the dose present in tissues, but 0.2% of the sorbed dose remained in the tissues after 100 h. In addition, internal exposure to tetra-PCB was the greatest with ca. 85% of the total sorbed dose present in tissues after 72 h of administration. These results suggested that lower chlorinated PCBs can absorb rapidly, but also metabolize and eliminate relatively quickly. On the other hand, higher chlorinated PCBs penetrate slowly, but persist at the sites of exposure and therefore can slowly enter the systemic circulation. Recently, Abdallah et al.⁴⁴ used EPISKIN human skin equivalent tissues to mimic human dermal absorption of BDE-1, 8, 28, 47, 99, 153, 183, and 209 and also found that lower brominated congeners achieved faster dermal penetration, whereas higher brominated congeners displayed greater accumulation within the skin tissue. Furthermore, Hughes et al.⁴⁵ used skin from hairless adult female mice (SKH1), mounted in flow-through diffusion cells, to study the absorption of ¹⁴C-BDE-209 and ¹⁴C-tris(1,3-dichloro-2-propyl)phosphate (TDCPP). BDE-209 showed low penetration (0.3%) to the receptor fluid, with up to 20% of the dose remaining in skin after 24 h. TDCPP penetrated more (39–57%) to the receptor fluid than BDE-209, with 28–35% of the dose remaining in the skin. In another human *ex vivo* skin study,⁴⁶ the absorbed doses of α -, β -, and γ -hexabromocyclododecanes (HBCD) and tetrabromobisphenol A were less than 7%, whereas 23–31% of the administered doses remained in the skin tissues.

These dermal absorption results showed that for congeners of the same homologue, their dermal absorption decreases with increasing molecular weight and K_{ow} and decreasing water solubility. Although the above-mentioned fractional absorption approach is widely used in dermal exposure assessment, it may underestimate the fraction absorbed as it does not consider the effect of loading (e.g., thin or thick surface loads) on dermal absorption.⁴⁷ Nevertheless, even heavy molecular weight flame retardants may become bioavailable upon sufficiently long exposure. On the other hand, the aforementioned results were obtained from dermal absorption via solvent-dosing; however, dermal uptake from gaseous flame retardants are deemed similar because they are related through the solvent–air partition coefficient.

■ EFFECTIVENESS OF DERMAL DECONTAMINATION

Previous dermal absorption studies by solvent-dosing revealed that hand washing and body cleaning with water or aqueous

solutions containing detergents may not be able to effectively reduce human exposure to gaseous pollutants via dermal uptake.^{43–45} Dennerlein et al.⁴⁸ recently showed that skin cleaning with purified water reduced 28–65% of the doses of hydrofluoric acid and anisole in the stratum corneum and epidermis/dermis. On the other hand, cleaning by water-soaked cotton swabs was ineffective in reducing the penetrated amounts of 1,4-dioxane, as compared to control experiments. Therefore, skin tissues may still be subject to the risk of exposure to contaminants even upon cleaning.

■ “WASH-IN” EFFECT

“Wash-in” effect refers to enhanced dermal penetration of chemicals during skin decontamination by water, water and soap or solvents, due to increased skin permeability and systemic absorption.⁴⁹ For example, the recoveries of ¹⁴C-1,1,1-trichloro-2,2-bis(4-chlorophenyl)ethane (DDT) in receptor fluids quickly reached a plateau and persisted until a second increase occurred when soap water rinse of the skin specimens was conducted at 24 h after exposure (Figure 3).⁵⁰ However,

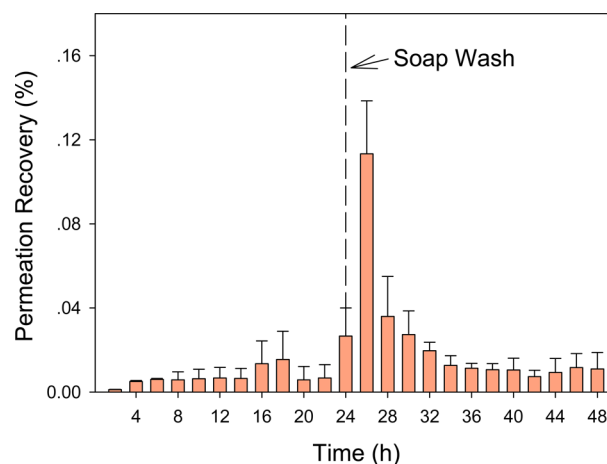


Figure 3. Wash-in effects for ¹⁴C-*p,p'*-DDT in rat skin tested *in vitro* (taken from Moody et al.⁵⁰). Note that the permeation recovery was calculated by the ¹⁴C-*p,p'*-DDT levels in the receiver solutions dividing the dose application rate.

wash-in effect related to flame retardants has not been adequately addressed. Although its mechanisms remain unclear,⁴⁹ “wash-in” effect may have toxicological significance, which is especially important during dermal exposure to gaseous and particle contaminants.

■ FOLLICULAR PENETRATION

The skin appendages (sweat glands and hair follicles) occupy only 0.1% of the total human skin surface, but can provide shunt pathways through the stratum corneum and even enhance skin penetration, because they are surrounded by a close network of blood capillaries, stems and dendritic cells.⁵¹ For example, hair follicles absorbed caffeine nearly 10 times faster than the stratum corneum, with no observable delay compared to an approximately 10 min delay for the stratum corneum.⁵¹ Also, intensive skin massage during washing can facilitate the transport of topically applied substances, for example, octylmethoxycinnamate (a UV filter), into the hair follicles.⁵² Nanoparticles could also penetrate much deeper into the hair follicles than fluorescent dye of nonparticle form, that

is, fluorescein-containing hydrogel, if massage was applied.⁵³ Another attribute is that the hair follicles can serve as an efficient reservoir for topically applied substances, for example, nanoparticles were found to store in the hair follicles for up to 10 days, whereas substances of nonparticle form were not detectable after 4 days.⁵³ Therefore, this attribute plays an important role in follicular penetration, especially for particle-bound substances, allowing hazardous substances to penetrate deep into the skin.

Clearly, percutaneous vapor absorption needs to be adequately examined as to better characterize and minimize the exposure risk by developing effective mitigation strategies. Particularly, all aforementioned factors for dermal absorption are physiologically related and must be addressed through an interdisciplinary approach. Furthermore, the compositional profiles and concentrations of gaseous effluents from combustion fume are known to depend on the types of electrical/electronic devices, combustion fuel and conditions and oxygen supply.⁵⁴ However, most studies thus far have focused on particulate SVOCs in e-waste recycling zones, with relatively less attention to gaseous pollutants. This underscores the need to acquire data about gaseous emissions from e-waste recycling sites and adjacent areas, in particular air concentrations measured by personal monitoring techniques to collect reliable exposure information. Moreover, the role of clothes and fabrics in altering dermal exposure to airborne pollutants has not been adequately considered. In this regard, cross-contamination during laundering, drying (e.g., under sunlight and by dryer) and storage processes, as well as the likelihood for adverse health effects resulted from reemission of sorbed pollutants from fabrics, must be thoroughly examined. Finally, several factors, such as the type of detergents used and stratum corneum structural heterogeneity, may also mediate the effectiveness for removing sorbed pollutants and should be included in any dermal uptake assessment.

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Notes

The authors declare no competing financial interest.

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