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What Are the Sources of Exposure to Eight Frequently Used Phthalic Acid Esters in Europeans?

Matthias Wormuth,[1] Martin Scheringer,[1*] Meret Vollenweider,[1] and Konrad Hungerbühler[1]

Phthalic acid esters (phthalates) are used as plasticizers in numerous consumer products, commodities, and building materials. Consequently, phthalates are found in human residential and occupational environments in high concentrations, both in air and in dust. Phthalates are also ubiquitous food and environmental contaminants. An increasing number of studies sampling human urine reveal the ubiquitous phthalate exposure of consumers in industrialized countries. At the same time, recent toxicological studies have demonstrated the potential of the most important phthalates to disturb the human hormonal system and human sexual development and reproduction. Additionally, phthalates are suspected to trigger asthma and dermal diseases in children. To find the important sources of phthalates in Europeans, a scenario-based approach is applied here. Scenarios representing realistic exposure situations are generated to calculate the age-specific range in daily consumer exposure to eight phthalates. The scenarios demonstrate that exposure of infant and adult consumers is caused by different sources in many cases. Infant consumers experience significantly higher daily exposure to phthalates in relation to their body weight than older consumers. The use of consumer products and different indoor sources dominate the exposure to dimethyl, diethyl, benzylbutyl, diisononyl, and diisodecyl phthalates, whereas food has a major influence on the exposure to diisobutyl, dibutyl, and di-2-ethylhexyl phthalates. The scenario-based approach chosen in the present study provides a link between the knowledge on emission sources of phthalates and the concentrations of phthalate metabolites found in human urine.

KEY WORDS: Consumer exposure; consumer products; exposure modeling; exposure pathways; phthalates; plasticizers

1. INTRODUCTION

Recent screening studies in industrialized countries for contaminants in human urine samples have revealed the population's ubiquitous exposure to various plasticizers, the group of phthalic acid diesters (phthalates).(1–8) The presence of phthalate metabolites in the human body requires identification of the dominating sources of exposure as well as of the pathways causing this exposure. Several million tons of phthalates are used per year worldwide in the production of soft polyvinyl chloride (PVC) and other plastics that are contained in many consumer products.(9–11) Phthalates are not chemically bound to the products and are released continuously into the air or leach from the products.(12,13) As a consequence, phthalates contaminate indoor environments(14–17) and human food(18–29) and belong to the ubiquitous environmental contaminants today.(30–35) The most important plasticizers are di-2-ethylhexyl phthalate (DEHP),

1 Institute for Chemical and Bioengineering, ETH Zurich, Zurich, Switzerland.
* Address correspondence to Martin Scheringer, Institute for Chemical and Bioengineering, Swiss Federal Institute of Technology Zurich, ETH Hönggerberg, HCI G127, 8093 Zurich, Switzerland; tel: +41-44-6323062; fax: +41-44-6321189; martin.scheringer@chem.ethz.ch.

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Table I. Phthalates Investigated in the Present Study

Abbreviation	Ester Groups	Formula	CAS No.	Molecular Weight	Tolerable Daily Intakes (TDIs) in μg/kg bw/day
DMP	Dimethyl	$C_{10}H_{10}O_4$	131-11-3	194.2	n.a.
DEP	Diethyl	$C_{12}H_{14}O_4$	84-66-2	222.2	10,000*[122]
DiBP	Diisobutyl	$C_{16}H_{22}O_4$	84-69-5	278.4	100[97]
DnBP	Di-n-butyl	$C_{16}H_{22}O_4$	84-74-2	278.4	100[97]
BBzP	Butylbenzyl	$C_{19}H_{20}O_4$	85-68-7	312.4	850[97]
DEHP	Di-(2-ethylhexyl)	$C_{24}H_{38}O_4$	117-81-7	390.6	50[97]
DINP	Diisononyl	$C_{26}H_{42}O_4$	28553-12-0 68515-48-0	418.6 (418.6–432.6)	150[97]
DIDP	Diisodecyl	$C_{28}H_{46}O_4$	26761-40-0 68515-49-1	446.7 (432.7–446.7)	250[97]

*TDI deduced from NOAEL by applying an extrapolation factor of 100.

diisononyl phthalate (DINP), and diisodecyl phthalate (DIDP), which made up more than 75% of the total European phthalate consumption of more than 1 million tons in 2003.[36] Other important phthalates investigated in the present study are dimethyl phthalate (DMP), diethyl phthalate (DEP), diisobutyl phthalate (DiBP), di-n-butyl phthalate (DnBP), and butylbenzyl phthalate (BBzP) (Table I).

The ubiquitous exposure to phthalates might be critical because toxicological studies have demonstrated considerable adverse effects of phthalates and their metabolites to human health. DEHP, DINP, DIDP, BBzP, DnBP, and DiBP are reproductive toxicants affecting mainly the male reproductive system in mammals.[37–41] DEHP shortens the duration of human pregnancy[42] and disrupts or modulates the human endocrine system.[43–46] Increased exposure to DEP is correlated with a decrease in human sperm quality.[46–47] Recently, high dust concentrations of DEHP were associated with an increased asthma risk in children, while high dust concentrations of BBzP were associated with an increased incidence of rhinitis and eczema in children.[50]

Phthalates entering the human body are rapidly hydrolyzed to the monoesters and then further metabolized and excreted with urine and feces.[51–54] The screening for phthalate metabolites in human urine is therefore a promising method to study human exposure to the mother compounds. Most urine screening studies in the past relied on phthalate monoesters.[3] For phthalates with short alkyl chains, monoesters represent the major human metabolites. However, in the case of DEHP, DINP, and DIDP, the monoesters are further metabolized. Consequently, exposure estimates based on urinary monoester concentrations alone might underestimate the population's actual exposure to these phthalates.[1,4–6,55]

Urine screening studies in the year 2000 presented for the first time a comprehensive picture of the population's frequent and sometimes high exposure to phthalates.[3] However, such studies showing the ubiquitous exposure of consumers need to be complemented by analyses of sources and pathways leading to the observed exposure. The main objective of the present work, hence, is to investigate in detail European consumers' daily exposure to eight frequently used phthalates—DMP, DEP, DiBP, DnBP, BBzP, DEHP, DINP, and DIDP—and to give an insight into the pathways of exposure (Fig. 1). To this end, the scenario-based risk assessment approach (SceBRA) is used.[56] The usefulness of scenarios in exposure analysis has been demonstrated in the assessment of workplace exposure to chlorinated solvents[57] and consumer exposure to musk fragrances.[58] A broad set of scenarios is generated in SceBRA that represents typical and realistic exposure situations for 15 different oral, dermal, and inhalation exposure pathways. Phthalate exposure occurring via these routes is estimated for seven age and gender groups, including infants, toddlers, children, teenagers, and adults. The total consumer exposure to the eight phthalates is calculated from the sum of single exposure estimates for the 15 investigated pathways.

Only few other works have so far investigated consumer exposure to phthalates via different pathways. Müller *et al.*[59] used the EUSES model[60] to calculate point estimates of exposure via food and air and basic scenarios to simulate product-related exposure situations. These scenarios considered the Danish population's exposure from toys, baby food,

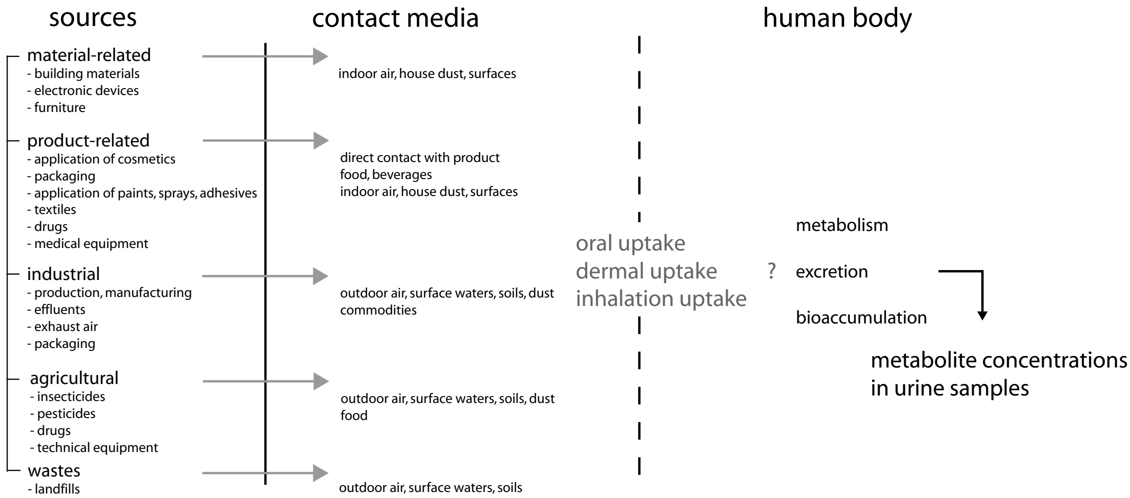

Fig. 1. Consumers are exposed to phthalates via different sources. Measurements of concentrations of phthalate metabolites in urine samples have demonstrated the ubiquitous consumer exposure to these plasticizers.

indoor air and dust inhalation, plastic gloves, paints, adhesives, and nail polish.

In the EU risk assessments that are available for five phthalates, worst-case estimates for consumer exposure are made on the basis of scenarios.[61–65] However, the choice of exposure scenarios is not clearly documented in the reports. The U.S. Center for the Evaluation of Risks to Human Reproduction (CERHR) has evaluated the risks to human reproduction posed by the most important phthalates.[66–70] These evaluation reports include a general summary of possible exposures of the general population.

Two Canadian exposure assessments for DEHP and DnBP[71,72] provide estimates of daily uptake of the substances via air, drinking water, food, ingested soil, and child care articles. They are supplemented by a recent study on five phthalates using a probabilistic assessment method.[73]

2. METHODS

The present work analyzes scenarios that reflect oral, dermal, and inhalation pathways causing consumer exposure to phthalates (Fig. 1). To cover all relevant pathways, data from a variety of sources of different quality had to be used. For most input parameters, minimum, mean, and maximum values or 5th, median, and 95th percentile values are determined, depending on the quality of available data. For a few parameters only point estimates are used. This section gives information on the kind of data used to generate input parameter values reported in this article, which are necessary to calculate consumer exposure. The set of equations needed in the exposure assessment is shown in Table II.

Based on external exposure estimates, daily internal exposure to eight phthalates (μg/kg bodyweight/day) is calculated with organ- and situation-specific uptake rates for seven age and gender groups: infants (0–12 months, 5.5 kg bw); toddlers (1–3 years, 13 kg bw); children (4–10 years, 27 kg bw); female adolescents (11–18 years, 57.5 kg bw); male adolescents (11–18 years, 57.5 kg bw); female adults (18–80 years, 60 kg bw); male adults (18–80 years, 70 kg bw).

2.1. Scenarios for Oral Exposure

2.1.1. Consumption of Food

Scenarios for food consumption are based on amounts of edibles consumed daily, the fraction of consumers eating these edibles regularly, and concentrations of phthalates measured in the edibles.

Amounts of edibles consumed daily and the fraction of consumers eating them are determined from food consumption surveys that used questionnaires and diaries. The mean daily amount of food consumed is calculated from European food surveys for infants,[74–76] toddlers,[77–79] children,[77–81] female and male adolescents,[77,78,81–83] and female and male adults[84–86] (Table III).

Table II. Equations Used to Calculate Body-Internal Consumer Exposure to Phthalates

Exposure Pathways	No.	Equations	Required Parameters, Units, Sources
Oral contact			
Food	1	$E_{food} = \frac{\sum_{i=1}^{n} C_{food_i} \cdot q_{food_i} \cdot CF_i}{bw} \cdot r_{uptake}$	C_{food} is phthalate concentration in edible i (mg/kg),[18–29,87,88] q_{food} is amount of edible i consumed daily (kg/day),[74–86] CF is fraction of population consuming edible i[74–86]
Dust	2	$E_{dust\_ing} = \frac{C_{dust} \cdot q_{dust\_ing}}{bw} \cdot r_{uptake}$	C_{dust} is phthalate concentration in dust (mg/kg),[15–17,92] q_{dust_ing} is amount of dust ingested daily (kg/day)[89–91]
Soil	3	$E_{soil\_ing} = \frac{C_{soil} \cdot q_{soil\_ing}}{bw} \cdot r_{uptake}$	C_{soil} is phthalate concentration in soil (mg/kg),[3035] q_{soil_ing} is amount of soil ingested daily (kg/day)[89–91]
Toys	4	$E_{toys\_ing} = \frac{S_{mouth} \cdot r_{release} \cdot t_{mouth} \cdot MF}{bw} \cdot r_{uptake}$	S_{mouth} is toy surface that is mouthed (cm^2),[97] $r_{release}$ is amount of phthalate per surface area and time that is released ($mg/cm^2/hr$),[97–100] t_{mouth} is time of mouthing (hr/day),[94–97] MF is fraction of toys containing phthalates[102]
PCPs	5	$E_{prod\_ing} = \frac{C_{prod} \cdot q_{prod\_ing}}{bw} \cdot r_{uptake}$	C_{prod} is phthalate concentration in personal care products (mg/kg),[9,103,104] q_{prod_ing} is amount of PCPs ingested (kg/day) based on assumption
Dermal contact			
PCPs	6	$E_{prod\_derm} = \frac{\sum_{i=1}^{n} C_{prod_i} \cdot q_{prod_i} \cdot f_{event_i} \cdot r_{ret_i} \cdot MF_i}{bw} r_{uptake}$	C_{prod} is phthalate concentration in product i (mg/kg),[9,103–104] q_{prod} is amount of product i used per application (kg),[58] f_{event} is frequency of use of product i (1/day),[58] r_{ret} is fraction of product i retained by skin,[58] MF is market fraction of product i containing phthalates[103–104]
Toys	7	$E_{toys\_derm} = \frac{C_{toy} \cdot D_{toy} \cdot T_{toy} \cdot A_{contact} \cdot t_{contact} \cdot MF}{bw} \cdot \frac{flux_{dermal}}{d_{Deisinger}}$	C_{toy} is phthalate concentration in toys (mg/kg),[10,99,102] D_{toy} is density of toy (kg/cm^3) based on assumption, T_{toy} is thickness of toy (cm),[99] $A_{contact}$ is skin surface area in dermal contact with toys (cm^2),[97] $t_{contact}$ is duration of contact (hr/day),[94–96] MF is market fraction of toys containing phthalates,[102] $flux_{dermal}$ is flux of phthalates from toys into human body ($mg/cm^2/hr$) based on DEHP flux,[120] $d_{Deisinger}$ is dose applied in experiments of Deisinger *et al.* (mg/cm^2)[120]
Textiles	8	$E_{textile} = \frac{C_{textile} \cdot w_{textile} \cdot A_{contact} \cdot t_{contact}}{bw} \cdot \frac{flux_{dermal}}{d_{Deisinger}}$	$C_{textile}$ is phthalate concentration in textiles (mg/kg),[27] $w_{textile}$ is weight of textiles (kg/m^2) based on assumption, $A_{contact}$ is total skin surface area in contact with textiles (m^2),[107] $t_{contact}$ is duration of contact (hr/day) based on assumption, $flux_{dermal}$ is flux of phthalates from textiles into human body ($mg/cm^2/hr$) based on DEHP flux,[120] $d_{Deisinger}$ is dose applied in experiments of Deisinger *et al.* (mg/cm^2)[120]
Gloves	9	$E_{gloves} = \frac{C_{gloves} \cdot w_{gloves} \cdot A_{contact} \cdot t_{contact} \cdot f_{dishes} \cdot MF}{bw} \cdot \frac{flux_{dermal}}{d_{Deisinger}}$	C_{gloves} is phthalate concentration in gloves (mg/kg)[10], w_{gloves} is weight of gloves (kg/cm^2) based on assumption, $A_{contact}$ is skin surface area in contact with gloves (cm^2)[89], $t_{contact}$ is duration of contact (hr)[92], f_{dishes} is frequency of dish washing (1/day)[92], MF is market fraction of gloves containing phthalates[10], $flux_{dermal}$ is flux of phthalates from gloves into human body ($mg/cm^2/hr$) based on DEHP flux,[120] $d_{Deisinger}$ is dose applied in experiments of Deisinger *et al.* (mg/cm^2)[120]
Paints, adhesives	10	$E_{paints\_dermal} = \frac{C_{spot} \cdot q_{spot} \cdot t_{contact} \cdot f_{painting}}{bw} \cdot \frac{flux_{dermal}}{d_{Deisinger}}$	C_{spot} is phthalate concentration in paint or adhesive (mg/kg),[115] q_{spot} is amount of paint or adhesive on the skin (kg),[114] $t_{contact}$ is duration of contact (hr),[114] $f_{painting}$ is frequency of paint or adhesive use (1/day),[114] $flux_{dermal}$ is flux of phthalates from products into human body ($mg/cm^2/hr$) based on DEHP flux,[120] $d_{Deisinger}$ is dose applied in experiments of Deisinger *et al.* (mg/cm^2)[120]
Particles	11	$E_{part\_derm} = \frac{C_{part} \cdot q_{part\_skin} \cdot A_{part} \cdot 0.15}{bw} \cdot r_{uptake}$	C_{part} is phthalate concentration in particles adhered to skin (mg/kg),[15–17,92] q_{part_skin} is amount of particles on skin (kg/cm^2), A_{part} is skin surface area in contact with particles (cm^2) based on assumption and,[107] 0.15 is fraction of chemicals in particles available for uptake[90]
Inhalation			
Indoor air, outdoor air	12	$E_{inh} = \frac{C_{air\_in} \cdot \sum_{i=1}^{n} (V_{inh\_act_i} \cdot t_i) + C_{air\_out} \cdot \sum_{j=1}^{m} (V_{inh\_act_j} \cdot t_j)}{bw} \cdot r_{uptake}$	C_{air_in} is phthalate concentration in indoor air (mg/m^3),[14–15] V_{inh_act} is activity-dependent inhalation volume (m^3/hr),[112] t is time spent on different activities (hr/day),[109–111] C_{air_out} is phthalate concentration in outdoor air (mg/m^3)[32–33]
Hair sprays, spray paints	13	$E_{inh\_spray} = \frac{C_{spray} \cdot t_{spray} \cdot r_{spray} \cdot f_{spray} \cdot t_{contact} \cdot V_{inh} \cdot 0.005}{V_{exp} \cdot bw} \cdot r_{uptake}$	C_{spray} is phthalate concentration in sprays (mg/kg),[115] t_{spray} is time of spraying (min),[114] r_{spray} is amount of droplets formed per time unit (kg/min),[114] f_{spray} is frequency of use of spray (1/day),[114] $t_{contact}$ is duration of contact with spray droplets (hr),[114] V_{inh} is inhalation volume (m^3/hr),[112] 0.005 is fraction of droplets that can be inhaled,[114] V_{exp} is volume around the consumer (m^3)[114]

E = the internal exposure to phthalates in mg/kg bodyweight/day; r_{uptake} = the fraction of the amount of phthalate transferred into the body. See Section 2.4.

Table III. Amounts of Food Consumed Daily; Amounts of Ingested Soil, Dust, and Personal Care Products (g/day)

	Infants		Toddlers		Children		Female Teens		Male Teens		Female Adults		Male Adults	
Food	Mean	*CF*	Mean	*CF*	Mean	*CF*	Mean	*CF*	Mean	*CF*	Mean	*CF*	Mean	*CF*
Pasta, rice	17.0	0.070	25.0	0.654	24.2	0.589	56.0	0.693	64.1	0.637	59.7	0.869	74.6	0.863
Cereals	52.0	0.580	21.7	0.727	18.1	0.689	23.6	0.930	21.9	0.890	25.5	0.753	29.3	0.750
Breakfast cereals											58.1	0.500	74.6	0.460
Bread	30.4	0.648	39.6	0.737	41.8	1.000	87.5	0.993	123.7	0.980	94.8	0.903	130.3	0.898
Biscuits, crispy bread	5.0	0.175	15.2	0.872							15.1	0.680	21.3	0.630
Cakes, buns, puddings	21.5	0.514	10.0	0.466	25.9	0.879	31.4	0.970	55.4	0.980	38.6	0.860	45.9	0.842
Bakeries, snacks	2.2	0.251	7.7	0.656	9.1	0.781	80.7	0.817	102.7	0.883	8.7	0.591	10.6	0.595
Milk, milk beverages	386.3	0.645	307.3	0.902	276.5	0.987	150.0	0.980	212.6	0.980	154.6	0.730	188.3	0.740
Cream					2.5	0.170	14.6		4.1		5.0	0.190	4.8	0.185
Ice cream	17.0	0.055	18.3	0.579	17.8		11.4		25.8		13.8	0.329	15.2	0.324
Yogurt	38.0	0.225	43.1	0.698	26.3	0.485	52.0		39.2		42.2	0.651	36.0	0.596
Cheese	7.5	0.375	5.6	0.572	7.6	0.574	51.8	1.000	77.6	0.990	31.8	0.927	34.1	0.937
Eggs	6.3	0.083	6.3	0.288	9.4	0.412	9.7	0.990	15.4	0.990	25.4	0.861	31.1	0.877
Spreads	3.0	0.280									29.6	0.330	35.4	0.370
Animal fats	3.0	0.280	2.2	0.264	2.3	0.284	3.7	0.880	3.8	0.840	7.0	0.794	16.5	0.789
Vegetable oils	3.0	0.280	7.1	0.394	10.3	0.474	21.1	0.437	26.5	0.410	13.6	0.799	17.6	0.811
Meat, meat products	21.5	0.290	27.3	0.368	28.8		68.0	1.000	76.4	1.000	88.5	0.948	117.1	0.949
Sausage	26.0	0.033	9.5	0.448	9.0	0.484	15.3	0.880	29.4	0.940	34.8	0.855	42.7	0.864
Poultry	14.7	0.444	4.5	0.329	8.2	0.447	13.5		23.6		37.0	0.825	59.5	0.874
Fish	5.2	0.096	10.0	0.325	5.1		22.9	0.940	30.8	0.930	47.6	0.781	55.5	0.768
Vegetables	35.8	0.478	56.1	0.916	72.0	0.830	144.1	0.970	137.0	0.910	187.3	0.998	198.2	0.998
Potatoes	21.9	0.390	54.8	0.783	53.4	0.927	58.6	0.533	66.7	0.600	96.7	0.930	122.5	0.912
Fruits	117.3	0.659	91.6	0.841	113.2	0.826	90.9	0.840	103.4	0.763	223.4	0.972	220.5	0.967
Nuts, nut spreads	1.5	0.069			1.5						4.8	0.542	6.1	0.522
Preserves, sugar	3.0	0.170	6.8	0.557	7.6	0.638	3.9		8.8		11.2	0.591	14.8	0.675
Confectionery	6.0	0.130	13.3	0.633	30.9	0.719	17.4	0.990	22.2	1.000	24.3	0.808	29.3	0.801
Spices					5.1		7.8		7.8		22.7	0.991	31.6	0.992
Soups, sauces					1.7	0.815	2.7		2.7		36.2	0.650	41.3	0.643
Juices	72.0	0.110	64.2	0.380	59.2	0.400	60.0	0.730	78.0	0.570	93.7	0.728	101.9	0.713
Tea, coffee	3.3	0.035	1.4	0.246	2.1	0.335	4.1	0.850	4.7	0.870				
Or coffee											13.9	0.813	17.2	0.820
Or tea											4.5	0.636	3.9	0.629
Soft drinks	16.7	0.100	450.0	0.670	416.1	0.825	290.7	0.780	384.0	0.863	423.1	0.457	518.4	0.507
Beer					1.9		186.3	0.157	267.7	0.337	83.1	0.391	280.4	0.678
Wine					1.0		5.0	0.730	14.0	0.830	66.2	0.663	115.0	0.629
Spirits					0.0		5.0	0.240	10.0	0.250	6.0	0.320	10.3	0.428
Tap water					255.4	0.069	346.4		346.4		461.1	0.918	428.9	0.877
Bottled water					194.3		272.2		272.2		270.6	0.461	270.8	0.441
Commercial infant food	85.5	0.370												
Infant formulas	485.0	0.370	53.0	0.500	13.6	0.116								
Breast milk	336.0	0.115												
Other media than food														
House dust	0.05	1	0.05	1	0.01	1	0.001	1	0.001	1	0.001	1	0.001	1
Soil	0.06	1	0.06	1	0.06	1	0.06	1	0.06	1	0.06	1	0.06	1
PCPs	0.05	1	0.05	1	0.05	1	0.05	1	0.025	1	0.05	1	0.025	1

CF = fraction of the population regularly consuming the food.
Sources: See text.

Phthalate concentrations have been measured in diverse edibles[18–22] and in infant formula and mother's milk[19–29,87,88] (the problem of sample contamination during analysis generally has been addressed). The number of food quality studies over the last decade from Europe is limited, so that here reports from North America and Asia are also considered. Minimal, mean, and maximal phthalate concentrations in mg per kg food are determined (Table IV).

Table IV. Phthalate Concentrations in Various Foods (mg/kg) as Used in the Scenario Calculations

	DMP			DEP			DiBP			DnBP			BBzP			DEHP			DINP		
Food	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Pasta, rice	0	0	0	0	0	0.01700	0.00150	0.021	0.158	0.002	0.010	0.36	0	0	0.025	0.0000	0.012	0.17	0	0	0
Cereals	0	0	0	0	0.00650	0.02000	0.01000	0.109	0.180	0.074	0.565	2.10	0.013	0.015	0.017	0.0700	0.574	1.70	0	0	0
Breakfast cereals	0	0	0	0	0.00650	0.02000	0.01000	0.109	0.180	0.074	0.565	2.10	0.013	0.015	0.017	0.0700	0.574	1.70	0	0	0
Bread	0	0	0	0	0.00600	0.01740	0	0.060	0.232	0.007	0.032	5.13	0	0	0.440	0.0261	0.068	1.96	0	0	0
Biscuits, crispy bread	0	0	0	0	0	0	0	0.007	0.020	0	0.130	0.42	0	0.028	0.088	0.1020	0.547	1.10	0	0	0
Cakes, buns, puddings	0	0	0	0	0	0	0	0.007	0.020	0	0.130	0.42	0	0.028	0.088	0.1020	0.547	1.10	0	0	0
Bakeries, snacks	0	0	0	0	0	0	0.04800	0.154	0.260	0	0.011	1.17	0	0	0.530	0.0094	0.214	4.42	0	0	0
Milk, milk beverages	0	0	0.02800	0	0	0.01000	0	0	0.016	0	0.015	0.03	0	0	0.000	0.0085	0.040	0.17	0	0	0
Cream	0	0	0	0	0	0	0	0.002	0.010	0	0.037	0.70	0	0.005	0.030	0.1800	0.224	0.32	0	0	0
Ice cream	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1650	0.242	0.39	0	0	0
Yoghurt	0	0.01167	0.03500	0	0	0	0	0	0	0	0	0	0	0	0	0	0.051	0.09	0	0	0
Cheese	0	0	0	0	0.00233	0.00700	0	0	0	0	0.056	0.30	0	0.014	0.039	0.0410	0.496	1.23	0	0	0
Eggs, egg spreads	0	0	0	0	0	0	0	0.050	0.100	0.034	0.067	0.10	0.010	0.050	0.090	0.2830	0.442	0.60	0	0	0
Animal fats	0	0	0	0	0.00900	0.01800	0.01200	0.030	0.048	0	0.046	0.19	0	0.011	0.056	0.9130	1.447	2.83	0	0	0
Vegetable oils	0	0	0	0	0.00500	0.00925	0	0.020	0.067	0	0	0.88	0	0	0.357	0	0.404	2.08	0	0	0.046
Meat, meat products	0	0	0	0	0	0.01760	0	0.007	0.053	0.024	0.075	0.11	0	0	0.072	0.0248	0.207	0.76	0	0	0.011
Sausages	0	0	0	0	0	0	0	0	0.027	0.001	0.004	0.17	0	0	0.005	0.0380	0.064	0.75	0	0	0.007
Poultry	0	0	0	0	0.00500	0.01000	0	0.030	0.060	0	0.100	0.20	0	0.015	0.030	0.2850	0.518	0.70	0	0	0
Fish, seafood	0	0.00030	0.01678	0	0.00254	0.00851	0.00015	0.001	0.025	0.005	0.008	0.38	0	0.002	0.005	0.0023	0.013	0.29	0	0.0004	0.035
Vegetables	0	0	0	0	0.00667	0.00667	0	0	0	0	0.033	0.03	0	0	0	0	0.140	0.14	0	0	0
Potatoes	0	0	0	0	0.00900	0.00900	0	0.005	0.005	0	0	0	0	0	0	0	0.076	0.08	0	0	0
Fruits	0	0	0	0	0	0	0.00800	0.030	0.052	0.016	0.028	0.05	0	0	0	0.0300	0.069	0.12	0	0	0
Nuts, nut spreads	0	0	0.02100	0	0.00750	0.02330	0	0.045	0.232	0.043	0.218	17.46	0	0	0.021	0.1430	0.810	19.86	0	0	0
Preserves, sugar	0	0	0	0	0.00350	0.00700	0	0	0	0	0.603	1.60	0	0	0	0.0340	0.623	1.80	0	0	0
Confectionery	0	0	0	0	0	0.00560	0	0.012	0.069	0	0.075	7.89	0	0	0.037	0.0784	0.278	4.64	0	0	0
Spices	0	0.05600	0.21700	0	0.11675	0.46000	0.01000	0.541	1.840	4.980	7.493	12.68	0	0.417	1.620	1.3000	2.598	3.74	0	0	0
Soups, sauces	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0.00	0	0	0
Juices	0	0	0	0	0	0	0	0	0	0	0	0.02	0	0	0	0	0.020	0.06	0	0	0
Tea, coffee	0	0	0	0	0	0	0	0.006	0.006	0	0	0	0	0	0	0	0.008	0.01	0	0	0
Or coffee	0	0	0	0	0	0	0	0.006	0.006	0	0	0	0	0	0	0	0.008	0.01	0	0	0
Or tea	0	0	0	0	0	0	0	0.006	0.006	0	0	0	0	0	0	0	0.008	0.01	0	0	0
Soft drinks	0	0	0	0	0	0	0	0	0	0	0.005	0.19	0	0	0.001	0	0.018	0.08	0	0	0
Beer	0	0	0	0	0	0	0	0	0	0	0.023	0.07	0	0	0	0	0.041	0.11	0	0	0
Wine	0	0	0	0	0	0	0	0	0	0	0.148	0.66	0	0.001	0.002	0	0.009	0.02	0	0	0
Spirits	0	0	0	0	0	0	0	0	0	0	0	0.01	0	0	0.001	0	0.000	0.03	0	0	0
Tap water	0	0	0	0	0	0	0	0	0	0	0.001	0.00	0	0	0	0	0.012	0.03	0	0	0
Bottled water	0	0	0	0	0	0	0	0	0	0	0.001	0.00	0	0	0	0	0.012	0.03	0	0	0
Commercial infant food	0	0	0	0	0	0	0	0	0	0	0.013	0.05	0	0.004	0.017	0	0.283	1.64	0	0.0548	0.097
Infant formulas	0	0	0	0	0	0	0	0	0	0.008	0.068	0.25	0	0.001	0.002	0.0175	0.110	0.22	0	0	0
Mother's milk	0	0	0	0	0	0	0	0	0	0	0.015	0.05	0	0	0	0	0.034	0.11	0	0	0

Note: DIDP is not shown because it is only contained in seafood.
Sources: See text.

2.1.2. Ingestion of Dust and Soil

Scenarios simulating the ingestion of dust and soil combine amounts of dust and soil ingested daily with concentrations of phthalates in these media.

Infants and toddlers are known to incidentally ingest small amounts of dust and soil daily.(89–91) Amounts are estimated on the basis of trace element concentrations in human feces. Minimal, mean, and maximal amounts of ingested dust and soil are calculated from the available data (Table III). Here, it is assumed that children ingest 16.7% and teenagers and adults 1.1% of the amounts of dust ingested by infants and toddlers.(90) In contrast, we assume that all consumers ingest the same amounts of soil;(89–91) the phenomenon of pica children is not considered.

Phthalate concentrations in dust of European homes have been frequently measured.(15–17,92) The diameter of particles investigated and the pretreatment of dust samples can differ in these studies. Minimum, mean, and maximum phthalate concentrations are determined (Table V). Concentrations of high molecular weight phthalates in natural and agriculturally used soils were determined;(30) here, minimal, mean, and maximal concentrations (Table V) are calculated from single measurement values,(93) which are reported as summarized values in Reference 30. Concentrations of low molecular weight phthalates in greenhouse soils were studied;(30,35) here, minimal, mean, and maximal concentrations of DMP, DEP, and DiBP in soils are deduced from these data (Table V).

2.1.3. Mouthing Behavior of Infant Consumers

Scenarios for the mouthing of plastic objects use information on the duration of daily mouthing, the contact area of objects with the children's mouths, the release of phthalates from objects per time unit, and the phthalate-containing fraction of PVC objects on the market.

Infants, toddlers, and young children mouth diverse objects frequently and with varying duration.(94–97) Minimal, mean, and maximal durations are determined from the available data sets, which include information on mouthing also of objects other than PVC articles (Table VI).

The surface area of objects in contact with the infant's mouth varies considerably. The EU uses a default value for the contact area of 10 cm^2,(97) and this assumption is also used here.

Phthalates are released from PVC products depending on the duration and the way of mouthing (sucking and biting). Due to ethical reasons, this release was not studied directly in children. One study used adult volunteers to test phthalate release from PVC toys.(98) However, most studies relied on tests with artificial saliva and mechanical agitation.(97–100) Minimal release rates are taken from Rastogi *et al.*,(100) mean release rates are calculated from References 97–100, and maximal release rates are provided by CSTEE,(97) Fiala *et al.*,(98) and Rijk and Ehlert(99) (Table VI).

The use of DnBP, BBzP, DEHP, DINP, and DIDP in toys intended for infant consumers younger than 3 years was prohibited in the EU in 1999.(101) We assume that a fraction of toys lower than one still contains phthalates (*MF* in Table VI).(102)

2.1.4. Ingestion of Personal Care Products

Here, it is assumed that consumers incidentally ingest small amounts of personal care products (PCPs). Scenarios for ingestion of PCPs use information on amounts of products ingested daily and on phthalate concentrations in such products.

Because no information is available on how much PCPs are ingested daily, a worst-case assumption is used here: infants, toddlers, children, and female teenagers and adults ingest 50 mg product per day; male teenagers and adults ingest 25 mg product per day. The higher amounts ingested should reflect the more careless use of PCPs by infant consumers and the more frequent use of PCPs by female consumers.

Data sets on concentrations of phthalates in PCPs are of varying quality. On one hand, information is available on highest-use levels of DMP, DEP, and DnBP in various products.(9) On the other hand, studies measured phthalate concentrations in European retail PCPs.(103,104) It is here assumed that only shampoos, cosmetics, and skin care products are incidentally swallowed by consumers. Minimum, mean, and maximum concentrations of phthalates in these products are given in Table V.

2.2. Scenarios for Dermal Exposure

2.2.1. Use of PCPs

Scenarios for the use of PCPs are generated according to a simple dermal exposure model.(105) They include the frequency of use of PCPs, the concentrations of phthalates in products, the amounts of products used per application, the fraction of

Table V. Phthalate Concentrations in Different Media as Used in the Scenario Calculations

Media	Unit		DMP	DEP	DiBP	DBP	BBP	DEHP	DINP	DIDP
Dust	mg/kg	Min	0.1	0.3	6.6	9.5	3.1	137	11.3	4.7
	mg/kg	P50	0	3.2	22.4	48	16	699	56	33
	mg/kg	Mean	1.1	26	84	98	84	1,198	176	73
	mg/kg	P95	1.8	114	130	311	416	3,470	674	240
Soil	mg/kg	P5	0	0	0	0.0004	0.0001	0.0012	0.001	0.0005
	mg/kg	P50	0.0001	0.0001	0.0007	0.002	0.0003	0.011	0.007	0.003
	mg/kg	Mean	0.0001	0.0001	0.0007	0.005	0.001	0.0222	0.014	0.007
	mg/kg	P95	0.0013	0.0013	0.0013	0.015	0.003	0.067	0.057	0.028
Indoor air	ng/m^3	Min	125	10	9.7	194	0.0	46	0.5	0.3
	ng/m^3	P50	384	422	61	720	7.0	200	2.2	1.3
	ng/m^3	Mean	1,108	535	86	1,153	25	304	6.9	2.8
	ng/m^3	Max	13,907	5,481	990	5,586	575	615	1,293	363
Outdoor air	ng/m^3	Min	0	0	0	3.2	0	0.6	0	0
	ng/m^3	P50	0	0	0	11.9	0	2.8	0	0
	ng/m^3	Mean	0	3.9	0	22.3	1.1	10.0	0	0
	ng/m^3	Max	0	125	0	45	6	51.5	0	0
Gloves	mg/kg	Min	0	0	0	0	20,000	230,000	407,100	162,850
	mg/kg	Mean	0	0	0	0	26,750	338,333	417,850	167,150
	mg/kg	Max	0	0	0	0	33,000	420,000	428,600	171,400
Paints	mg/kg	Min	188	33	485	1,000	6,788	1,818	545	303
	mg/kg	Mean	1,033	33	2,667	5,500	37,333	10,000	3,000	1,667
	mg/kg	Max	1,879	33	4,848	10,000	67,879	18,182	5,455	3,030
Adhesives	mg/kg	Min	550	550	550	550	5,500	55,000	55,000	55,000
	mg/kg	Mean	41,400	2,200	33,600	36,900	26,700	44,000	39,200	18,300
	mg/kg	Max	55,000	5,500	55,000	55,000	55,000	55,000	55,000	55,000
Deodorant	mg/kg	Min	1	22	0	2	0	8.6	0	0
	mg/kg	Mean	678	400	0	128	0	8.6	0	0
	mg/kg	Max	2,000	3,930	0	200	0	8.6	0	0
Perfumes	mg/kg	Min	2	67	0	1	1	7	0	0
	mg/kg	Mean	4,316	9,400	0	297	8	15	0	0
	mg/kg	Max	17,000	49,500	0	890	29	130	0	0
Aftershaves	mg/kg	Min	2,000	900	0	900	0	0	0	0
	mg/kg	Mean	2,000	8,980	0	5,450	0	0	0	0
	mg/kg	Max	2,000	20,000	0	10,000	0	0	0	0
Hair styling	mg/kg	Min	0.2	8	0	1	1	1	0	0
	mg/kg	Mean	4,666	96	0	39	16	17	0	0
	mg/kg	Max	20,000	5,915	0	160	46	41	0	0
Shampoo	mg/kg	Min	900	8	0	70	0	0	0	0
	mg/kg	Mean	4,672	1,250	0	70	0	0	0	0
	mg/kg	Max	10,000	2,000	0	70	0	0	0	0
Skin care	mg/kg	Min	0	1.49	0	0	0	0	0	0
	mg/kg	Mean	0	900	0	0	0	0	0	0
	mg/kg	Max	0	9,300	0	0	0	0	0	0
Nail care	mg/kg	Min	0	1,000	0	8,000	0	0	0	0
	mg/kg	Mean	0	15,250	0	60,000	0	0	0	0
	mg/kg	Max	0	50,000	0	150,000	0	0	0	0
Makeup	mg/kg	Min	8	0.5	0	900	0	0	0	0
	mg/kg	Mean	17	1,049	0	5,300	0	0	0	0
	mg/kg	Max	50	4,000	0	10,000	0	0	0	0
Baby shampoo	mg/kg	Min	0	1	0	0	0	0	0	0
	mg/kg	Mean	0	101	0	0	0	0	0	0
	mg/kg	Max	0	300	0	0	0	0	0	0
Baby lotions, creams, oils	mg/kg	Min	0	0.3	0	0	0	0	0	0
	mg/kg	Mean	0	0.3	0	0	0	0	0	0
	mg/kg	Max	0	0.3	0	0	0	0	0	0
Other baby preparations	mg/kg	Min	0	500	0	0	0	0	0	0
	mg/kg	Max	0	500	0	0	0	0	0	0
	mg/kg	Mean	0	500	0	0	0	0	0	0
Ingested products, adults	mg/kg	Min								
	mg/kg	Mean	1,563	1,066	0	1,790	0	0	0	0
	mg/kg	Max	3,350	5,100	0	3,357	0	0	0	0
Ingested products, infants	mg/kg	Min	0	0.1	0	0	0	0	0	0
	mg/kg	Mean	0	1	0	0	0	0	0	0
	mg/kg	Max	0	300	0	0	0	0	0	0

Sources: See text.

Table VI. Phthalate Contents in Children's Products, Release Rates, and Mouthing Times

Release Rate from PVC ($\mu g/cm^2/min$)						
	Minimum	Mean	Maximum	Sources	Remarks	*MF*
DnBP	0.000	0.001	0.002	97, 100	Mechanical agitation using artificial saliva; only samples with low DnBP content considered	0.11
BBzP	0.000	0.002	0.004	97, 100	Mechanical agitation using artificial saliva; no maximum reported	0.09
DEHP	0.000	0.050	0.236	98–100	Mechanical agitation using artificial saliva; experiments with human volunteers	0.32
DINP	0.000	0.206	0.359	98–99	Mechanical agitation using artificial saliva; experiments with human volunteers	0.72
DIDP	0.000	0.162	0.277	97, 99	Mechanical agitation using artificial saliva; no maximum reported	0.04

Mouthing Time (min/day)					
	Minimum	Mean	Maximum	Sources	Remarks
Infants	0	91.9	292.4	94–96	All objects included
Toddlers	0	69.4	349.9	94–96	All objects included
Children	0	3.2	55	96	All objects included; data only for children younger than 5 years (reported values multiplied by 0.286)

MF = phthalate-containing market fraction.[102]
Sources: See text.

products retained by the skin after use and the phthalate-containing fraction of products on the market.

The use of PCPs by adult consumers is simulated using mean and maximum frequencies of use per day; minimal, mean, and maximal amounts of products applied; and mean fractions of products retained by the skin.[58] Teenagers' mean frequencies of use of products in Table VII were determined from a German market survey.[106] Infant consumers use other products than teenagers and adults with other frequencies.[107] PCPs made for children's use generally contain only DEP in lower concentrations than other PCPs[9] (Table V).

2.2.2. *Dermal Contact with Other Products, Soil, and Dust*

Consumers are in dermal contact with diverse products that contain phthalates. On one hand, contact with products such as textiles, cushions, and toys is frequent and lasts for a long time each day. Consumers are also exposed to small amounts of dust and soil that remain on their skin a long time. On the other hand,

Table VII. Behavioral Parameters Used to Simulate the Use of PCPs

	Amount Applied per Use, mg			Fraction Retained	Frequency of Use of Products, 1/day								
					Infants, Toddlers, Children			Female Teens	Male Teens	Female Adults		Male Adults	
Product	Minimum	Mean	Maximum	Mean	Minimum	Mean	Maximum	Mean	Mean	Mean	Maximum	Mean	Maximum
Deodorant	500	1,300	3,000	1				0.73	0.5	0.43	2	0.29	2
Perfume	650	700	750	1				0.26	0.18	0.29	1.5	0.12	1
Aftershave	1,200	1,200	1,200	1					0.16			0.14	1
Hair styling	3,700	7,500	10,000	0.05				0.49	0.16	0.43	2	0.05	2
Shampoo	8,000	12,100	16,400	0.01				0.56	0.52	0.43	2	0.43	2
Skin care	3,000	4,625	7,000	1				0.64	0.16	0.34	2	0.32	1.25
Nail care	280	1,300	3,060	0.25				0.13		0.11	1		
Makeup	490	490	490	1				0.32		0.18	1		
Baby lotion		1,400		1	0.38	1.19	2						
Baby oil		1,300		1	0.14	1.57	3						
Baby cream		1,400		1	0.43	1.72	3						
Baby powder		800		0.5	0.35	4.39	8.43						
Baby shampoo		500		0.01	0.11	0.27	0.43						

Sources: See text.

contact with some products, such as adhesives, paints, and gloves, is infrequent and lasts for short periods of time. Detailed analysis of these dermal pathways in the present study has shown that they cause in most cases insignificant daily exposure in relation to other pathways investigated here.

Only the use of plastic gloves can cause dermal exposure that results in significant internal exposure to some high molecular weight phthalates. In the scenarios simulating dermal contact with plastic gloves, we assume that teenagers and adults use gloves when doing the dishes. The frequency of dishwashing per day (0 as minimum, 0.63 as mean, 5 as maximum) and the duration per event in minutes (1 as minimum, 11 as mean, 60 as maximum) are taken from a Dutch observational study.(108) Concentrations of phthalates in gloves and the phthalate-containing fraction of gloves available on the market (Table V) are taken from a Danish report.(11) It is assumed here that the total surface area of both hands is covered with gloves for the total duration of dishwashing; surface areas of the hands are taken from USEPA.(107)

2.3. Scenarios Simulating Inhalation Exposure

2.3.1. Inhalation of Indoor and Outdoor Air

The scenarios for inhalation exposure take into account the time that consumers spend in various microenvironments, the concentrations of phthalates in air (including particles available for inhalation), and activity-dependent inhalation volumes.

Daily time-location activity patterns of adult consumers have been investigated in an Europe-wide study.(109) Time-location activity patterns for infant consumers and adolescents have been derived from national European studies.(110,111) Here, it is assumed that all activities take place inside of buildings except the categories "sports, outdoor activities," "being outdoors," and "commuting, travel." We assign a level of physical activity to each category in the time-location activity patterns. Activity-dependent inhalation volumes in liter per minute were calculated from data taken from Adams(112) (Table VIII).

Recent investigations of the quality of indoor environments demonstrated the ubiquitous contamination of indoor air with phthalates.(14–17) Minimum, mean, and maximum concentrations in indoor air are calculated from these data (Table V). Concentrations include the fraction of phthalates bound to suspended particles that are available for inhalation. Measured indoor air concentrations are unavailable for DINP and DIDP. Here, indoor air concentrations of DINP and DIDP are calculated on the basis of mean concentrations of suspended particulate matter,(113) and minimal, mean, and maximal concentrations of DINP and DIDP in house dust (Table V).

Only four of the investigated phthalates have been detected in outdoor air.(32,33) Minimum, mean, and maximum concentrations of DEP, DnBP, BBzP, and DEHP in outdoor air are calculated from these data (Table V).

Concentrations of phthalates in the air of cars and other transportation vehicles can be relatively high due to evaporation of phthalates from PVC interiors. Systematic investigations of phthalate concentrations in vehicles are missing; here, they are assumed to be equal to phthalate concentrations in indoor air.

2.3.2. Spray Paints

Sprays generate aerosols that are inhaled by consumers. In the scenarios, spray paints are infrequently used by teenagers and adults (two times per year, which is 0.0055 per day).(114) The mean duration of spraying is 4 minutes and the mean contact time with aerosols is 15 minutes.(114) A typical fingertip dispenser generates 25 grams of spray per minute and the fraction of particles that are available for inhalation is 0.005.(114) The volume around the consumer is 1 m^3.(114) Concentrations of phthalates in spray paints are determined from a Swiss product register(115) (Table V).

2.4. Conversion of External Exposure to Internal Exposure

The scenarios provide estimates of the external consumer exposure to phthalates. External exposures resulting from oral, dermal, and inhalation pathways are converted into internal exposures by applying uptake rates of different organs (r_{uptake}, fraction of amount of phthalates that is transferred into the human body).

2.4.1. Gastrointestinal Uptake

All rates for gastrointestinal uptake of phthalates by humans are shown in Table IX. Phthalate uptake through the human gastrointestinal tract has been studied for DnBP, BBzP, and DEHP by means of urinary concentrations of primary monoester metabolites.(51) In these experiments, uptake of DnBP is 64–73% of the oral exposure. Gastrointestinal uptake

Table VIII. Physiological Characteristics and Time-Activity Data of Consumers

Activity	Duration Spent on Activities Each Day (min/day)						Activity Level	Inhalation Volumes (L/min)			
	Infants	Toddlers	Children	Teens	Female Adult	Male Adult		Infants, Toddlers, Children		Female Teens/ Adults	Male Teens/ Adults
Sleeping	669.5	731.5	609	547	508	497.5	Lying, sleeping	6.19	7.51	7.12	8.93
Napping, resting	249.5	155.5			21	22	Lying, sleeping	6.19	7.51	7.12	8.93
Eating	79	88	67	72	82.5	80.4	Sitting	6.48	7.28	7.72	9.3
Personal care			48	50	55	53.6	Sitting, standing		7.89	8.04	9.975
Employment			5	180	153	242	Sitting, standing		7.89	8.04	9.98
Study			229	84			Sitting		7.28	7.72	9.3
Housework, shopping			45	74	219.5	97.5	Standing		8.49	8.36	10.65
Childcare			1	14	31	12	Sitting, standing		7.89	8.04	9.98
Voluntary work			9	9	12.5	12.5	Sitting, standing		7.89	8.04	9.98
Social life			52	90	55.5	50	Sitting, standing		7.89	8.04	9.98
Entertainment			9	8	5.5	6	Sitting, standing		7.89	8.04	9.98
Sport, outdoor activity			29	20	54.5	57	Running		31.78	48.22	60.47
Hobbies			94	26	18	45	Sitting, standing, running		15.85	21.43	26.81
Reading			10	10	30.5	30.5	Lying, sitting		7.395	7.42	9.115
Watching TV, video			139	141	118.5	137.5	Sitting		7.28	7.72	9.30
Listening to music			8	11			Lying, sitting		7.4	7.42	9.12
Commuting, travel			76	96	59	73	Sitting, walking		13.695	17.41	24.47
Being outdoors	28.8	80.3					Lying, sitting, standing, walking	8.64	11.8		
Other	405.7	384.7			9.5	11.5	Sitting, standing	6.62	7.89	8.04	9.98

		Skin Surface Area (cm^2)						Air Inhalation Volumes (L/min)				
		Head	Arms	Hands	Legs	Feet	Total	Lying	Sitting	Standing	Walking	Running
Infants	Mean	414	312	121	469	149	2,280	6.19	6.48	6.76	10.82	n.a.
Toddlers	Mean	826	667	295	1,245	359	5,380	6.19	6.48	6.76	10.82	n.a.
Children	Mean	1,107	1,146	463	2,381	621	8,580	7.51	7.28	8.49	15.83	31.78
Female teens	Mean	1,283	2,165	789	4,687	1,093	14,630	7.12	7.72	8.36	22.26	48.22
Male teens	Mean	1,326	2,237	815	4,844	1,130	15,110	8.93	9.30	10.65	29.52	60.47
Female adults	Mean	1,110	2,300	820	5,460	1,140	16,900	7.12	7.72	8.36	22.26	48.22
Male adults	Mean	1,300	2,910	990	6,400	1,310	19,400	8.93	9.30	10.65	29.52	60.47

Sitting, standing: 50% of both activities, hence average of both inhalation rates; sitting, standing, running: 1/3 of the three activities, hence 1/3 of each inhalation rate; lying, sitting: 50% of both activities, hence average of both inhalation rates; sitting, walking: 50% of both activities, hence average of both inhalation rates; lying, sitting, standing, walking: 1/4 of the four activities, hence 1/4 of each inhalation rate.
Sources: See text.

of DMP, DEP, and DiBP is assumed here to be the same as for DnBP.[116] In Reference 51, gastrointestinal uptake of BBzP is 69–78% of the oral exposure. For DEHP, a gastrointestinal uptake rate of 15% was determined in humans in an earlier study.[52] Recent studies, however, have demonstrated that DEHP uptake through the gastrointestinal tract is close to 100%.[53–54] Uptake of DEHP is assumed here to be 15–95% of the external oral exposure. Gastrointestinal uptake of DINP has been studied in rats and renal excretion was between 40–60%.[117] The total uptake of DINP from the oral dose might have been 75–90%.[117] Here, a similar metabolism of DINP in rat and human being is assumed and uptake of DINP is assumed to be 75–90% of the oral exposure. Uptake of DIDP here is the same as that of DINP.

2.4.2. *Dermal Uptake of Cosmetic Ingredients, Soil, and Dust*

Rates for dermal uptake of chemicals from PCPs, soil, and dust are shown in Table IX. Dermal uptake of phthalates has been studied in rats for phthalates by applying alcoholic phthalate solutions to

Table IX. Uptake Rates Used to Convert External Exposure into Internal Doses, Denoted by r_{uptake} in Table II

	DMP	DEP	DiBP	DBP	BBP	DEHP	DINP	DIDP
Oral uptake rates [fraction of applied dose]								
Min	0.64	0.64	0.64	0.64	0.67	0.153	0.75	0.75
Mean	0.685	0.685	0.685	0.685	0.725	0.552	0.825	0.825
Max	0.73	0.73	0.73	0.73	0.78	0.95	0.9	0.9
Dermal uptake rates: cosmetics [fraction of applied dose]								
Min (rat)	0.06	0.05	0.05	0.1	0.04	0.005	0.003	0.004
Max (rat)	0.075	0.24	0.12	0.12	0.06	0.01	0.006	0.007
Min (adult)	0.0086	0.0071	0.0071	0.0143	0.0057	0.0007	0.0004	0.0006
Mean (adult)	0.0096	0.0207	0.0121	0.0157	0.0071	0.0011	0.0006	0.0008
Max (adult)	0.0107	0.0343	0.0171	0.0171	0.0086	0.0014	0.0009	0.0010
Min (child)	0.017	0.014	0.014	0.029	0.011	0.001	0.001	0.001
Mean (child)	0.0193	0.0414	0.0243	0.0314	0.0143	0.0021	0.0013	0.0016
Max (child)	0.021	0.069	0.034	0.034	0.017	0.003	0.002	0.002
Dermal uptake rates: soil and dust [fraction of applied dose]								
Min (adult)	0.000424	0.000354	0.000354	0.000707	0.000283	3.54E-05	2.12E-05	2.83E-05
Mean (adult)	0.000477	0.001025	0.000601	0.000778	0.000354	5.3E-05	3.18E-05	3.89E-05
Max (adult)	0.00053	0.001697	0.000849	0.000849	0.000424	7.07E-05	4.24E-05	4.95E-05
Min (child)	0.000849	0.000707	0.000707	0.001414	0.000566	7.07E-05	4.24E-05	5.66E-05
Mean (child)	0.000955	0.002051	0.001202	0.001556	0.000707	0.000106	6.36E-05	7.78E-05
Max (child)	0.001061	0.003394	0.001697	0.001697	0.000849	0.000141	8.49E-05	0.000099
Dermal uptake rates: films [μg/cm^2/hr]								
Mean (rat)	2.34	4.08	2.64	3.84	1.68	0.24	0.14	0.18
Mean (adult)	0.33	0.58	0.38	0.55	0.24	0.03	0.02	0.03
Mean (child)	0.67	1.17	0.75	1.10	0.48	0.07	0.04	0.05
Inhalation uptake rates [fraction of applied dose]								
Mean (adult)	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Mean (child)	1	1	1	1	1	1	1	1

Sources: See text.

the skin.[117,118] For DEP, uptake through human skin is lower than through rat skin by a factor of seven.[119] Here, for all eight phthalates, uptake through human skin is assumed to be lower by a factor of seven than through rat skin. In addition, we assume that the skin of infant consumers is twice as permeable as the skin of teenagers and adults.[90]

The same rates of chemical uptake from PCPs are applied to the uptake of chemicals from particles adhered to the skin. However, the soil or dust matrix reduces the uptake of chemicals to about 15%.[90] Additionally, we here assume that only one-third of the affected skin surface area is in contact with particles.

2.4.3. Dermal Uptake of Chemicals from Films

The dermal uptake of phthalates from films on the skin such as gloves, textiles, or toys is modeled here with uptake rates obtained from experiments with plasticized PVC films (containing 40 weight-% DEHP) on rat skin.[120] The uptake is a function of the applied dose. An average uptake rate through the skin of 0.24 μg/cm^2/hr has been reported for DEHP.[120] Uptake rates for the other phthalates (Table IX) are calculated from the relative ratios of dermal uptake rates for cosmetics shown in Table IX. Again, it is assumed that uptake through the human skin is by a factor of seven lower for all phthalates and that the skin of infant consumers is twice as permeable as the skin of teenagers and adults.

2.4.4. Uptake of Chemicals Through the Respiratory Tract

Rates of phthalate uptake subsequent to inhalation are unknown. Hence, an uptake rate of 100% for infants, toddlers, and children and of 75% for teenagers and adults as proposed in the EU risk assessments for several phthalates[61–65] is used.

3. RESULTS

Fig. 2 shows exposure to the eight phthalates for different consumer groups. The most striking result of

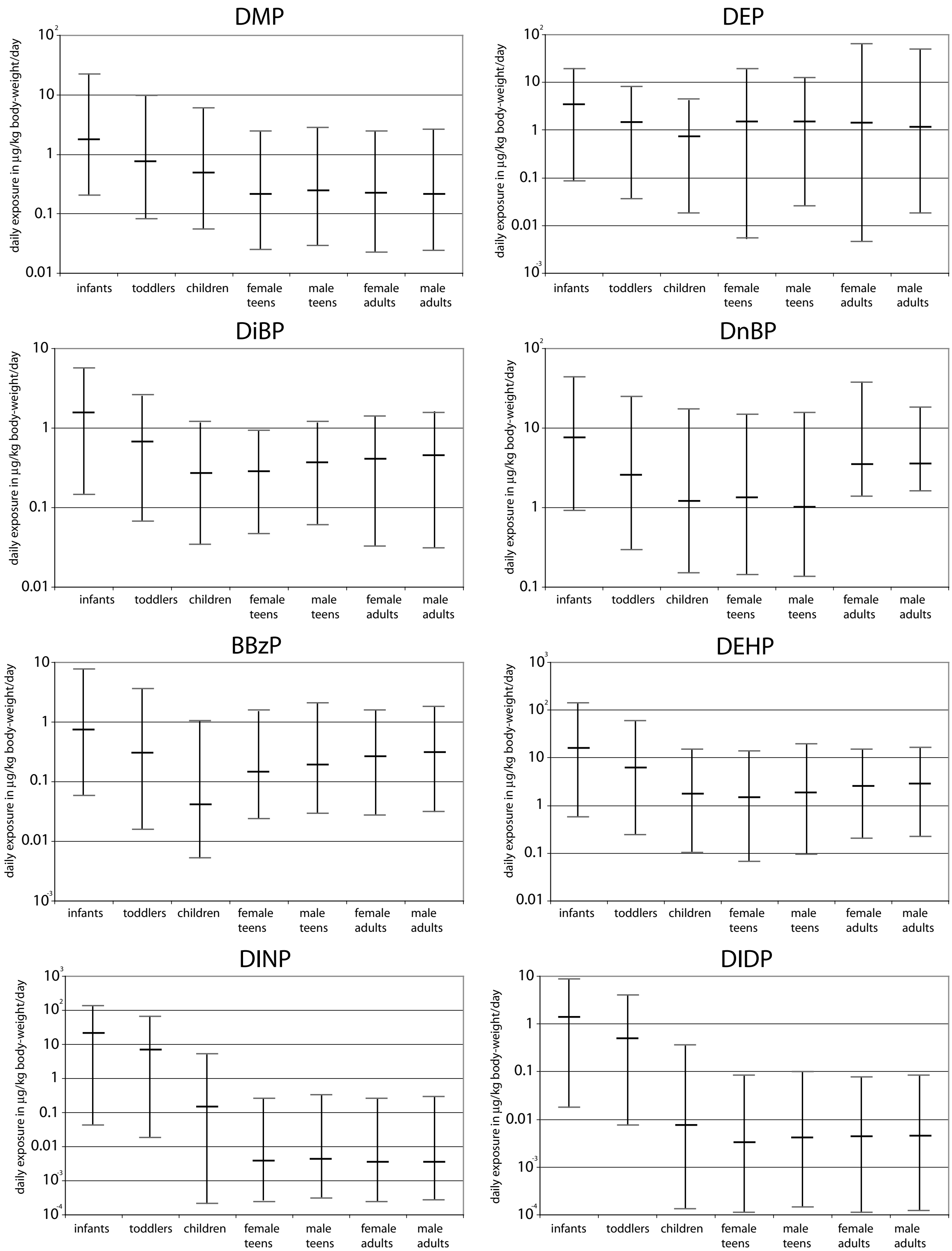

Fig. 2. Daily internal exposure to eight phthalates (in μg/kg body-weight/day) in seven consumer groups. Minimal, mean, and maximal exposure estimates are shown.

the present study is that infants and toddlers experience highest daily exposures in relation to their body weight to all eight investigated phthalates, including those known as reproductive toxicants in mammals. This is valid for the mean daily exposure as well as for the maximal exposure (except for DEP and DnBP). Infants and toddlers have a mean daily exposure to DINP and DIDP that is higher than the maximum exposure to these phthalates in all other consumer groups investigated. Their maximum exposure to DEHP and DINP is higher than 100 μg/kg bw/day and stems mainly from the mouthing of soft plastic toys and the ingestion of food and dust. The maximal exposure predicted with our scenarios is considerably higher than the tolerable daily intake (TDI) for DEHP and in the range of the TDI for DINP.[97]

For the ranges of exposure, in contrast, no such consistent picture can be drawn. The range of exposure to DMP, DiBP, and DIDP is similar in all consumer groups. For DEP, the range of exposure is increasing from infant consumers to teenagers and adults. A decreasing range of exposure from infant consumers to adults can be observed for DnBP, BBzP, DEHP, and DINP.

The contribution of various sources to exposure to the eight phthalates is shown in Fig. 3 for different consumer groups. The sources of exposure to BBzP, DINP, and DIDP differ significantly between infant consumers and teenagers/adults. Dust is the main source of BBzP in infants and toddlers (>70%); additional exposure to BBzP results from food (20%) and air (5%). Food is a major source of BBzP in children (73%) and additional exposure is due to contaminated indoor air (26%). Spray paints cause exposure to BBzP in teenagers (>70%) and adults (40%); also food is a major source of BBzP in teenagers (>20%) and adults (60%).

More than 90% of the exposure to DINP of infants, toddlers, and children is due to the mouthing of soft plastics. Teenagers and adults are exposed to DINP mainly from dust (>30%), air (around 30%), spray paints (20%), and gloves (>10%).

Exposure to DIDP of infants, toddlers, and children is caused by the mouthing of soft plastic (55–82%). An additional source of DIDP in infants and toddlers is dust (40%). Children experience additional exposure to DIDP from the inhalation of contaminated indoor air (16%). Teenagers and adults are exposed to DIDP from food (55–70%), dust (>10%), air (9–13%), gloves (5–7%), and spray paints (5–7%).

Exposure to DMP, DEP, DiBP, DnBP, and DEHP is caused by similar sources in all consumer groups (Fig. 3). Exposure to DMP is mainly caused by indoor air (almost 100% in infants, toddlers, and children and 70–90% in teenagers and adults) and PCPs (only in teenagers and adults, 10–20%).

In the case of DEP, more than 80% of the exposure to DEP is caused by the dermal application of PCPs, mainly fragrances and aftershaves, deodorants and skin creams, or by incidental ingestion of personal care products. Contaminated air is another important source of DEP causing up to 30% of the exposure.

For DiBP, food is the major source of exposure in all consumer groups (60% in infants and toddlers, >95% in teenagers and adults). In infants and toddlers, dust (30%) and contaminated indoor air (>8%) contribute significantly to exposure to DiBP.

All consumer groups experience exposure to DnBP from the consumption of food (40–90%). In infants, toddlers, and children, indoor air (20–40%) and dust (10%) are additional sources of DnBP. Teenagers are exposed to DnBP also from contaminated indoor air (14–22%). In teenagers and female adults, PCPs cause between 15% and 50% of the exposure.

Food is the most important source of DEHP in all consumer groups (50–98%); dust (>35%) and toys (8–9%) are additional sources of DEHP exposure in infants and toddlers.

4. DISCUSSION

Consistent patterns of exposure can be found for four of the eight phthalates investigated: indoor air causes most of exposure to DMP in all consumer groups. The application and the incidental ingestion of PCPs are the major sources of exposure to DEP in all consumer groups. Food is the dominating source of exposure to DiBP and DEHP in all consumer groups.

Concerning the remaining four phthalates, consumers can be divided into two classes with different exposure patterns and sources: infants and toddlers, on one hand, and teenagers and adults, on the other hand; children's exposure to phthalates is transitional. The differences between the two classes of consumers (infant consumers vs. teenagers, adults) and the similarities within each class are because of the age-dependent behaviors and related exposures (e.g., the mouthing of soft plastic and oral exposure, crawling on the floor and high oral exposure to dust in young consumers; the use of PCPs and exposure to DEP and DnBP in older consumers).

We can identify two classes of consumers exposed to BBzP, DINP, and DIDP because of a complete change in the sources of exposure. Various consumer

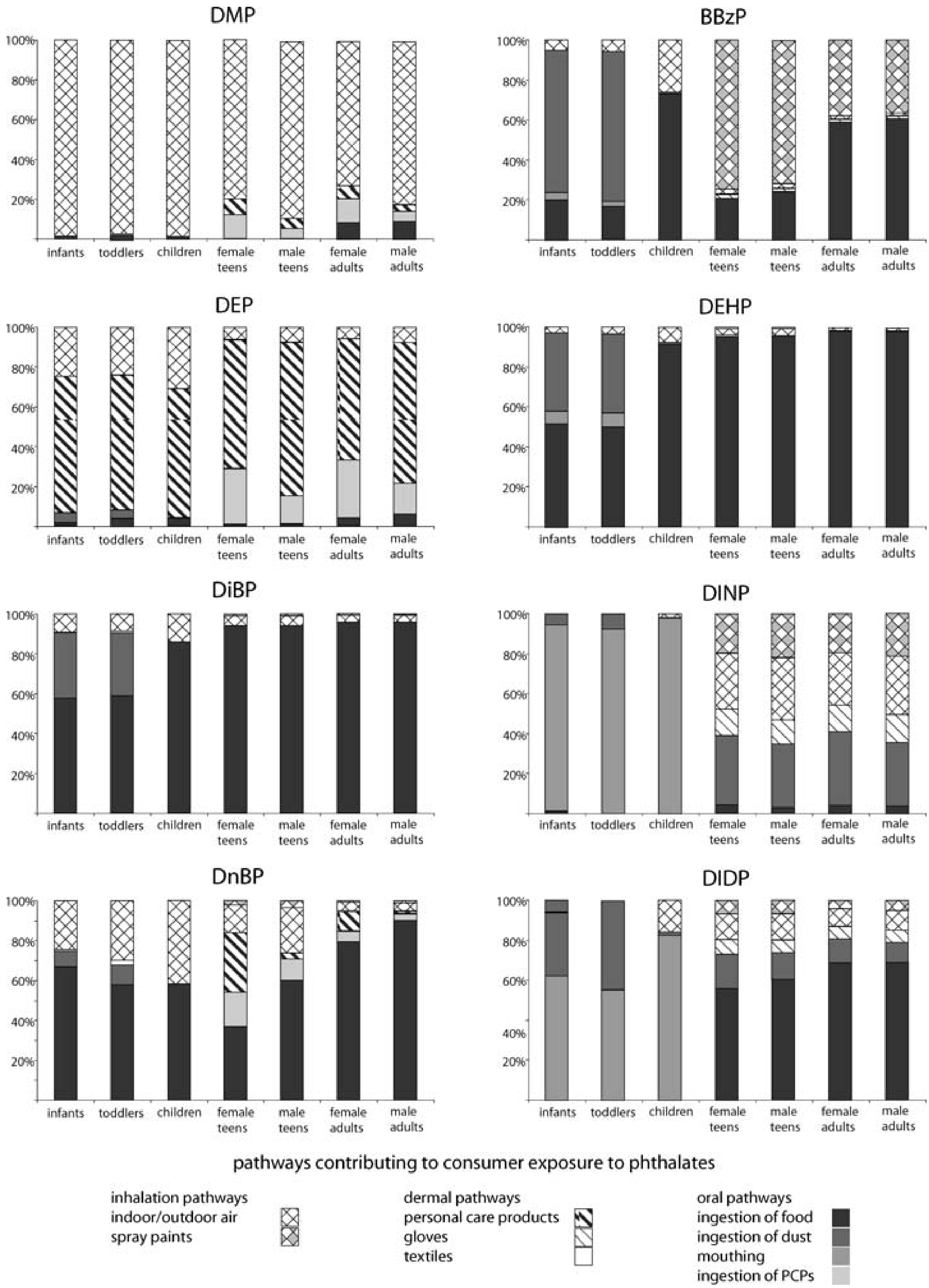

Fig. 3. Contributions of different sources to the mean total daily internal exposure to eight phthalates in seven age and gender groups.

products (such as toys, plastic gloves, and paints) and dust cause an important part of the exposure to these phthalates. Toys are frequently mouthed by infant consumers, leading to oral exposure to phthalates. Infants and toddlers ingest much higher amounts of dust than older consumers. The oral exposure pathway is characterized by an effective uptake of phthalates through the gastrointestinal tract. Therefore, infant consumers experience relatively higher daily exposure to BBzP, DINP, and DIDP (Fig. 2). Older consumers, in contrast, are exposed to BBzP, DINP, and DIDP from products that are rarely used (spray paints) or lead to dermal exposure (gloves) characterized by an ineffective uptake of phthalates. DINP is the most important substitute for DEHP in its applications today. It is probable that the exposure patterns of DINP and DEHP will become similar in the near future. Therefore, food might become a major source of exposure to DINP, leading to an increase in consumer exposure to this phthalate.

In contrast, we find the two classes of consumers differently exposed to DnBP because PCPs intended for the use of older consumers contain relatively high amounts of this phthalate, whereas PCPs for children are free of it. Hence, though food is the dominating source of exposure in all age groups, PCPs contribute remarkably to the exposure to DnBP of older consumers.

The uptake rates shown in Table IX demonstrate that the oral and inhalation pathways cause much more efficient uptake of phthalates into the human body than the dermal pathways. This observation leads to the question of how consumer exposure to phthalates can efficiently be reduced.

For all eight phthalates, exposure is, on one hand, due to the direct use of consumer products. An efficient strategy to reduce exposure is to avoid products containing high amounts of plasticizers such as soft plastic toys; these cause more than 90% of exposure to DINP of infants, toddlers, and children. Adult consumers might avoid highly fragranced cosmetic products such as perfumes or nail polishes, causing at least 65% of exposure to DEP in all age groups and 15–50% of exposure to DnBP in teenagers and female adults (see Fig. 3).

On the other hand, consumer exposure is indirectly connected to the use of plasticized products in households, which contaminate the residences. Exposure can be reduced by using building materials, commodities, and consumer products that contain lower amounts of phthalates. However, consumers only have the possibility to choose phthalate-free alternatives if the products are labeled in a clear and comprehensible manner.

In the case of DiBP, DnBP, BBzP, and DEHP, food is a major source of phthalates in humans. Here, it is more difficult to reduce consumer exposure. On one hand, phthalates in food have a diffuse environmental origin, which is caused by emissions from a variety of sources at all stages of the life cycle of phthalates (production, use, and disposal). On the other hand, phthalates migrate from the processing equipment (e.g., gloves, tubes, and pots) or the packaging (including imprints and adhesives) into the food. In this case, the food industry plays a major part in reducing consumer exposure to phthalates

4.1. Variability in the Exposure Estimates

The variability in the daily exposure to phthalates is considerable (Fig. 2). This is due to a complicated interplay between uncertainty and natural variability in the input parameters and the importance of different sources contributing to the total daily exposure.

Many input parameters are insufficiently known, especially concentration parameters, which depend on uncertain and variable conditions such as degradation or ventilation, leaching, or emission rates; or are confidential, such as phthalate contents in consumer products. Also, parameters describing the use of consumer products, such as frequencies of use or amounts used per application, are rarely available. Highly variable contact parameters such as consumers' physiology (body sizes and body weights, inhalation rates, uptake, and metabolism rates) and consumers' behavior show natural variability and, to a lesser extent, uncertainty.

The range of the total daily exposure is generally determined by the uncertainty and variability of the parameters that characterize the dominating exposure pathways (Fig. 3). In most cases, the same pathways are relevant under the assumptions of minimal, mean, or maximal input parameters.

The ratios of maximal to minimal exposure to phthalates are around a factor of 100 for most phthalates and consumer groups. Such ratios reflect the "normal" variability in contact parameters and the uncertainty in concentration parameters. However, considerably higher ratios of maximal to minimal exposures are found for DEP (for teenagers and adults) and for DINP and DIDP (for infants, toddlers, and children). Phthalate concentrations in ingested PCPs have the highest contribution to variance in DEP exposure (result not shown). We assumed a wide range of possible values for DEP concentrations in PCPs, because of inconsistent data from frame formulations[9] and measurements of concentrations in products.[103,104] Variance in exposure to DINP and DIDP of infants, toddlers, and children is mainly caused by highly variable duration of mouthing, rates of release of phthalates from plastics, and dust concentrations (results not shown).

Fig. 2 shows that the mean daily exposure to phthalates generally is relatively low with regard to the maximum exposure. Several of the contact-related parameters driving exposure, such as amounts of products used per application or amounts of consumed edibles, are log-normally distributed. The skewed distribution of input parameter values leads to skewed distributions of exposure estimates with mean values closer to the minimum exposure values in Fig. 2.

4.2. Model Evaluation

The exposure estimates presented here are compared to those of other studies to put them into perspective. First, exposure estimates are available from modeling studies and from EU risk assessment reports. Second, daily consumer exposure to phthalates can be deduced from measured concentrations of phthalate metabolites in human urine.[5–7]

Exposure estimates obtained from modeling studies vary considerably. Müller *et al.*[59] take into account several situations of product use leading to exposure to phthalates but consider only the external daily exposure. Their estimates are considerably higher than our estimates for daily internal exposure to phthalates.

The EU risk assessments of five phthalates assume worst-case conditions in the scenarios representing typical exposure situations.[61–65] Hence, the exposure estimates obtained from the scenarios are high in comparison with our estimates. We use realistic assumptions even for maximum parameter values. For example, we limit the fractions of products containing phthalates to values below 1.

The three studies available from Canada[71–73] neglected several routes, such as PCPs, soft plastic toys, and other consumer products, causing exposure to phthalates. Moreover, the study of Clark *et al.*[73] only provides external exposures. In contrast to our study, all three Canadian studies found that food was the most important source of phthalates in humans and that infants experience lower daily exposure to phthalates than other consumer groups.

In Table X, we compare our exposure estimates to exposure values deduced from measurements of urinary phthalate metabolite concentrations in the German population. Our estimates for adults are in good agreement with the measurement-based estimates for DEP, DnBP, BBzP, and DEHP.[5–7] Note that especially the maximum values (95th percentile values) derived from measurements and obtained with our approach are consistent, which shows that the assumptions made in the scenarios used to calculate exposure are reasonable.

Table X. Exposure (in μg/kg bw/day) Calculated from Urinary Concentrations of Phthalate Metabolites in Samples Taken from the German Population [5–7] (left) and Results from the Present Modeling Study (right) in Comparison

	Measured Data				Calculated Exposure Estimates		
Phthalate	min	P50	P95	max	min, P5	P50	max, P95
		Children				Children, our study	
DnBP	2.9	7.4		23.7	0.15	1.21	16.9
BBzP	0.2	1.8		9.2	0.005	0.04	1.08
DEHP	1.14	4.2	8.4	48.4	0.1	1.78	15.8
		Female adults				Female adults, our study	
DEP	0.7	3.9	32.6	96.9	0.005	1.43	64.9
DnBP	3	8.4	24.4	28.0	1.48	3.53	38.6
BBzP	0.2	0.9	4.0	6.8	0.03	0.27	1.65
DEHP	0.03	2.6	12.0	43.2	0.2	2.54	14.7
		Male adults				Male adults, our study	
DEP	0.3	1.4	28.1	30.0	0.02	1.15	50.9
DnBP	2.1	5.1	17.4	26.2	1.6	3.61	18.6
BBzP	0.2	0.7	3.0	4.5	0.03	0.31	1.9
DEHP	0.03	2.3	10.3	37.0	0.24	2.85	16.3

The present study slightly underestimates the exposure to phthalates of children. The underestimation can be due to data that reflect children's behavior inappropriately. In this case, more high-quality exposure-relevant data is desirable. Also, additional sources can contribute to the consumer exposure to phthalates that are not included in the present study. A recent investigation has shown that drugs can contain high amounts of DnBP and DEHP, which leads to oral exposure.[121]

5. CONCLUSIONS

The SceBRA method has proven suitable for developing a comprehensive and sufficiently detailed picture of the exposure to eight phthalates of European consumers. In the present study, especially infants and toddlers experience high daily exposures to phthalates. This finding may be critical as the most important phthalates are known to affect human reproduction and sexual development. In many cases, exposure can be attributed directly or indirectly to the use of consumer products containing phthalates or releasing phthalates into residences. The direct impact of soft plastic products on the exposure is evident in the case of infants' and toddlers' exposure to DINP. Consumer exposure to DEP is caused by the use of PCPs in all age groups. A strategy to reduce consumer exposure to phthalates is to restrict their use in childcare articles and PCPs. This strategy is applied in the European Union today. Additionally, a clear declaration of the ingredients of these products would enable consumers to choose phthalate-free alternatives.

Many plasticized consumer products, commodities, and building materials in households lead to a contamination of indoor air and dust. Low molecular weight phthalates such as DMP, DEP, and DnBP, which are used in PCPs and/or building materials such as sealing, are found in the indoor air at high concentrations. High molecular weight phthalates such as DEHP or DINP, which are used in floor and wall coverings or in upholsteries, can be found in house dust in high concentrations. Consumer exposure to these phthalates might be reduced by avoiding building materials and commodities containing large amounts of phthalates.

Food is a main source of DiBP, DnBP, and DEHP in consumers. In this case, consumers have very few possibilities to effectively reduce their exposure. However, the food industry can contribute to the reduction in consumer exposure by avoiding the use of phthalates in food packages (including adhesives, imprints) and in food processing equipment.

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