

Trends in Exposure to Chemicals in Personal Care and Consumer Products

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Abstract Synthetic organic chemicals can be used in personal care and consumer products. Data on potential human health effects of these chemicals are limited—sometimes even contradictory—but because several of these chemicals are toxic in experimental animals, alternative compounds are entering consumer markets. Nevertheless, limited information exists on consequent exposure trends to both the original chemicals and their replacements. Biomonitoring (measuring concentrations of chemicals or their metabolites in people) provides invaluable information for exposure assessment. We use phthalates and bisphenol A—known industrial chemicals—and organophosphate insecticides as case studies to show exposure trends to these chemicals and their replacements (e.g., other phthalates, non-phthalate plasticizers, various bisphenols, pyrethroid insecticides) among the US general population. We compare US trends to national trends from Canada and Germany. Exposure to the original compounds is still prevalent among these general populations, but exposures to alternative chemicals may be increasing.

Keywords Biomonitoring · Bisphenol · DINCH · Endocrine disruptors · Exposure · Insecticides · Pesticides · Phthalates

Introduction

People in our modern world are exposed to a wide range of man-made environmental chemicals, and animal studies suggest the potential for harmful effects to human health for many of these compounds [1•]. Some of these synthetic organic chemicals can be used in personal care and consumer products both as “active” (e.g., organophosphate insecticides) or “inactive” (e.g., phthalates, bisphenol A [BPA]) ingredients.

Many of these compounds are endocrine disruptors in animal studies, and evidence also is mounting on their potential effects on human health [2–4]. Therefore, given the scientific community and public’s concern over toxicity of these compounds, national, state, and local government entities in the USA and across the world have banned the use of some of these chemicals in a variety of products. Furthermore, environmental and public health organizations have advocated for the removal of certain chemicals from commerce. As a result, other chemicals might be entering the market and exposure to the original and the alternative compounds will change.

Understanding the extent of exposure to all of these environmental chemicals is of public health relevance. For exposure assessment, biomonitoring or measuring the concentrations of chemicals or their breakdown by-products in people is a useful tool [5, 6]. In this short review, we will present several case studies (phthalates, BPA, organophosphate insecticides) to highlight the usefulness of nationwide biomonitoring programs to track exposure trends to these compounds and their replacements since the early 2000s, particularly in the USA. If

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available, we will also compare the US data to data from other countries.

Examples of Population-Based Biomonitoring Surveys

Changes in reformulation of products and legislation may have implications for chemical exposures and potential human health risks. While substitute chemicals enter consumer markets, limited information exists on consequent trends in exposures to both the original and their corresponding replacements. Population-based biomonitoring programs or strategies could be useful to assess such trends. For this review, we will focus on two North American programs, the US National Health and Nutrition Examination Survey (NHANES) and the Canadian Health Measures Survey (CHMS), and two programs in Europe, the German Environmental Survey (GerES) and the German Environmental Specimen Bank (ESB).

In the USA, every year since 1999, NHANES, administered by the Centers for Disease Control and Prevention (CDC), recruits approximately 5000 participants who are representative of the US population [7]. NHANES participants undergo a physical examination and provide a detailed medical history. Furthermore, all NHANES participants 1 year of age and older provide blood; participants 6 years of age and older also provide one spot urine sample [8]. Some of the NHANES biological specimens are used to provide the most comprehensive assessment of the US general population's exposure to select environmental chemicals [9, 10]. Furthermore, biomonitoring NHANES data have been used to track exposure trends to several environmental chemicals, including heavy metals, phthalates, dichlorophenols, cotinine, pesticides, and polyfluoroalkyl substances [11, 12, 13•, 14–20].

Similar to NHANES in the USA, the German Federal Environment Agency conducts GerES (<http://www.umweltbundesamt.de/en/topics/health/assessing-environmentally-related-health-risks/german-environmental-survey-geres>), a nationwide population-representative study with the aim of evaluating exposures to environmental chemicals and their sources [21]. Since its inception in 1985 and until 1999, the first three GerES included only adults, GerES IV (2003–6) only children 3–14 years of age, and the ongoing GerES V (2014–7) will only sample children and adolescents (3–17 years). In addition, each year since 1985, ESB, also administered by the German Federal Environment Agency [21], collects and stores blood and one 24-h urine sample from approximately 120 students (20–29 years old) residing at four university cities throughout Germany (Munster, Greifswald, Halle/Saale, Ulm). ESB and GerES biological samples have been used to investigate exposures to

select environmental chemicals including bisphenol A (BPA) and phthalates [22–26, 27•, 28, 29].

CHMS, administered by Health Canada, is designed to provide representative data at the national level, and, since 2007, also includes a biomonitoring component. CHMS participants 6–79 years of age (3–79 since 2009 [30]) undergo a physical examination and provide questionnaire data and biospecimens [31]. Some of the CHMS biological samples are used to investigate exposures to select environmental chemicals including BPA, phthalates, and organophosphate and pyrethroid insecticides among Canadian children and adults [30].

NHANES, GerES, ESB, and CHMS have provided critical data to track temporal trends of exposure to phthalates, BPA, organophosphate, and pyrethroid insecticides and some of their replacements [13•, 19, 20, 22–25, 27•, 28–30].

Plasticizers: Phthalates and Phthalate Replacements

Phthalates have been widely used for decades in consumer goods and in personal care products [32]. High-molecular-weight phthalates (e.g., di-2-ethylhexyl phthalate [DEHP]) are primarily used as plasticizers of polyvinyl chloride (PVC), which, in turn, is used in numerous consumer products, flooring and wall coverings, toys, food contact applications, and medical instruments [33, 34]. Low-molecular-weight phthalates, such as di-*n*-butyl phthalate (DnBP), are used as solvents and plasticizers for cellulose acetate to make lacquers, varnishes, medication coatings, perfume, cosmetics, and other personal care products [35–42, 43•].

Exposure to phthalates in the developed world is pretty much universal [10, 22, 30, 44–50]. However, at high doses, exposure to several phthalates has been associated with a spectrum of male reproductive system disorders in animals [51–53]. On the other hand, evidence exists, albeit at times equivocal or contradictory, that environmental exposures to phthalates may also adversely affect human health [51, 53–58].

Because of widespread exposure and the potential of phthalates to negatively impact health, the European Union banned the use of certain phthalates in toys and childcare articles starting in 2001 [59] and Canada restricted the allowable concentrations of several phthalates in the soft vinyl of toys and child care articles in 2012 [60]. Similarly, in 2008, in the USA, the Consumer Product Safety Improvement Act banned the use of three phthalates (DnBP, butylbenzyl phthalate (BBzP), DEHP) in any amount >0.1 % in child care articles and placed an interim restriction on three other phthalates (di-isononyl phthalate (DiNP), di-isodecyl phthalate (DiDP), di-*n*-octyl phthalate (DnOP)) in toys that can be put in a child's mouth [61]. Subsequently, in 2014, the US federal government proposed to lift the interim prohibition for DnOP

and DiDP, but to permanently ban DiNP, and four additional compounds diisobutyl phthalate (DiBP), di-*n*-pentyl phthalate, di-*n*-hexyl phthalate, and dicyclohexyl phthalate at levels >0.1 % in any children's toy or child care article [62].

In addition to the legislative activity, several environmental and public health organizations have sought to reduce phthalate exposures by advocating for the removal of phthalates from personal care products and the use of potentially safer alternatives [63]. Furthermore, in the USA, in response to public concerns and consumers' demands (e.g., Campaign for Safe Cosmetics), Revlon and other major companies phased out phthalates used in nail polish and from their consumer product raw materials, finished products, and components, and many other cosmetic companies also pledged to eliminate phthalates from their products [64•].

Biomonitoring data may provide useful insights into these ongoing market changes. For example, DEHP, historically the most common PVC phthalate plasticizer, is being replaced with other phthalates (e.g., DiNP, DiDP) or non-phthalate plasticizers (e.g., di(isononyl)cyclohexane-1,2-dicarboxylate (DINCH[®])). DINCH[®] was introduced commercially in 2002 as a substitute for phthalate plasticizers in many PVC products particularly in sensitive application areas such as toys, medical devices, and food packaging. Of interest, metabolites of DINCH were not detected in urine specimens collected from German and US adults before 2002 [27•, 65•]. By contrast, the DINCH[®] metabolite cyclohexane-1,2-dicarboxylic acid-mono(hydroxy-isononyl) ester (MHNCH) was detected in 19.3 % of NHANES 2011–2012 participants' urine (range ≥ 0.4 –168.1 $\mu\text{g/L}$) [10]. Similarly, in 2012, MHNCH was detected in the urine of 98 % of German ESB student samples (range ≥ 0.05 –236 $\mu\text{g/L}$) [27•]. These data suggest that the general public in the USA and Germany is currently exposed to the non-phthalate plasticizer DINCH.

In a recent report using NHANES 2001–2010 data, Zota et al. showed that concentrations of the metabolites of DEHP peaked in 2005–2006 and declined 50 % by 2009–2010 while the concentrations of the metabolites of two of the potential DEHP phthalate replacements, namely DiNP and DiDP, increased 2.6 and 1.1 times, respectively [13•]. Similarly, Wittasek et al., using German ESB samples collected between 1988 and 2003, reported that median DEHP intakes, estimated from the DEHP metabolite concentrations, remained essentially unchanged (~ 4 $\mu\text{g/kg/day}$) between 1988 and 1993 but, since 1996, followed a downward trend to 2.4 $\mu\text{g/kg/day}$ in 2003 [28]. By contrast, daily DiNP median intakes doubled from 1998 (0.20 $\mu\text{g/kg/day}$) to 2003 (0.40 $\mu\text{g/kg/day}$); Wittasek et al. did not assess exposure to DiDP [28]. Although CHMS data exist only for 2007–2011 and CHMS measured fewer phthalate metabolites than NHANES during that time period, the 2007–2009 and 2009–2011 CHMS geometric mean concentrations of mono(2-ethyl-5-hydroxyhexyl) phthalate and mono(2-ethyl-5-oxohexyl)

phthalate, the two DEHP oxidative metabolites evaluated by both surveys, are remarkably similar to those reported by NHANES in 2007–2008 and 2009–2010, respectively (Fig. 1) [10, 30]. These data suggest that exposure to DEHP in the USA, Canada, and Germany may be decreasing, while exposure to DiNP, at least in the USA and Germany, where data exist, appears to be on the rise.

In addition to changes in exposure to high-molecular-weight phthalates, exposure to low-molecular-weight phthalates may also be changing. In the USA, during 2001–2010, the concentrations of the metabolites of BBzP, DnBP, and diethyl phthalate (DEP) declined 20–50 %, depending of the phthalate, while concentrations of the DiBP metabolite increased threefold [13•]. Wittasek et al. reported similar trends in Germany for the years 1988–2003 [28]. For example, the median daily intake of DnBP in 2003 (1.9 $\mu\text{g/kg/day}$) was considerably lower than between 1988 and 1993 (~ 7 $\mu\text{g/kg/day}$); for DiBP, a potential replacement of DnBP, median intakes increased slightly between 1988 (1.1 $\mu\text{g/kg/day}$) and 2003 (1.4 $\mu\text{g/kg/day}$) [28]. GerES IV biomonitoring data also suggest a decrease in median (95th percentile) urinary concentrations (in $\mu\text{g/L}$) of mono-*n*-butyl phthalate (MBP) (166 (624) vs 100 (364), respectively) for the 2001–2 GerES IV pilot (254 children 3–14 years) and the 2003–6 GerES IV (137 3–5 year olds); mono-isobutyl phthalate, the DiBP metabolite, was only measured in GerES IV [22, 24]. This apparent decline may be related, at least in part, to the fact that DnBP, the parent compound of MBP, was one of the first phthalates being restricted in all toys, childcare articles, and cosmetics in 2001 in the European Union [66]. Nonetheless, legislation is not the only factor affecting market trends. For instance, DEP is not regulated in the USA or in Canada; yet, NHANES data show a clear downward trend in exposure to DEP for all segments of the population [13•]; CHMS also suggests a decline in concentrations of monoethyl phthalate, the main DEP metabolite from 2007 to 2011 (Fig. 1) [30].

Taken together, these trends suggest that exposures to phthalates and their replacements may be affected by changes in production and use of these compounds in the consumer marketplace prompted, at least in part, from the combined efforts of legislators, advocacy groups, industry, and the general public [13•, 27, 28, 64].

Industrial Chemicals: BPA

BPA, one of the most studied synthetic chemicals in the past decades, is primarily used to manufacture polycarbonate plastic and epoxy resins and in the processing of PVC plastic and of thermal paper [67, 68].

Like for phthalates, exposure to BPA in the developed world is widespread [10, 25, 69–77]. Data from NHANES III, conducted from 1988 through 1994, first demonstrated

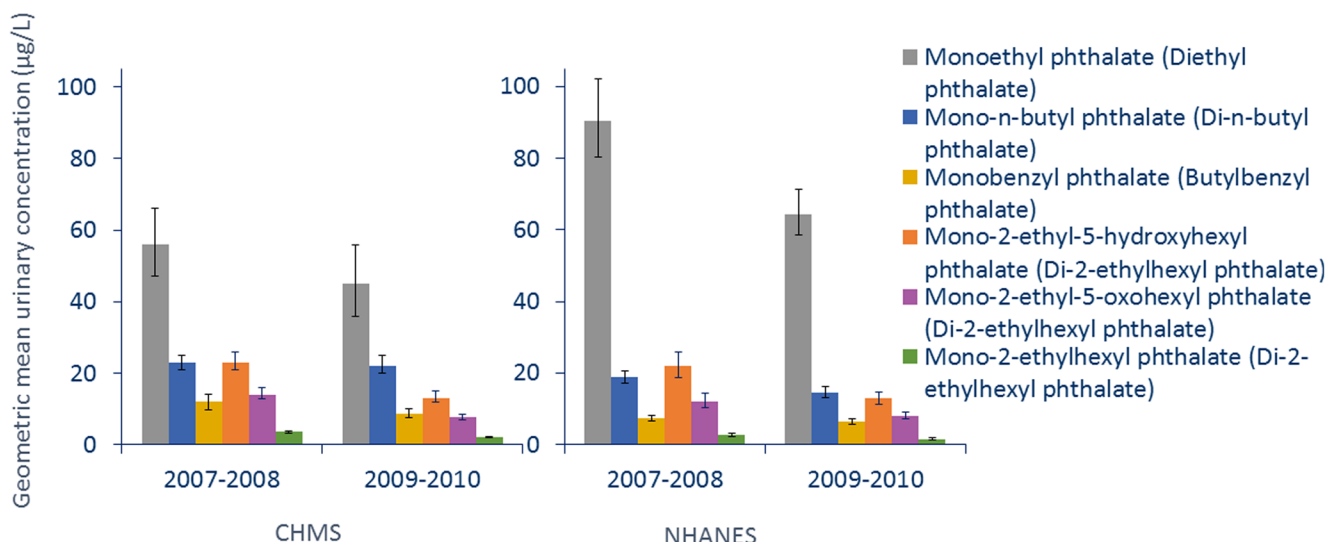


Fig. 1 Geometric mean urinary concentrations (in $\mu\text{g/L}$) of select phthalate metabolites measured in 2007–2008 and 2009–2010 as part of both the US National Health and Nutrition Examination Survey

(NHANES) and the Canadian Health Measures Survey (CHMS). The parent phthalate is given in *parenthesis* next to the name of the metabolite measured. *Error bars* indicate 95 % confidence intervals

exposure to BPA among US adults [78]. Subsequently, yearly NHANES data suggest that the majority of Americans have continued to be exposed to BPA since 2003–2004 when BPA became part of the NHANES ongoing biomonitoring program [10]. Of interest, from NHANES 2003–2004 to NHANES 2011–2012, geometric mean concentrations of BPA have decreased from 2.64 $\mu\text{g/L}$ (2.58 $\mu\text{g/g}$ creatinine) to 1.51 $\mu\text{g/L}$ (1.72 $\mu\text{g/g}$ creatinine) [10]. By contrast, the CHMS geometric mean urinary concentration of BPA in 2007–2009 and 2009–2011 did not change (1.2 $\mu\text{g/L}$) [30]. Similarly, using German ESB urine samples collected between 1995 and 2009 from University of Muenster students, Koch et al. reported that median BPA intakes had remained essentially unchanged (from 0.043 $\mu\text{g/kg/day}$ in 1995 to 0.039 $\mu\text{g/kg/day}$ in 2009) [25]. These data suggest a downward trend in exposure to BPA in the USA, but not in Germany or Canada. The reasons for the different trends are not clearly evident, although differences in calendar years surveyed, sampling strategies, and analytical methodologies may play a role. Future data will provide useful information to evaluate whether exposure to BPA continues to decline in the USA and whether the marketing of BPA-free products and bans enacted since the late 2000s in Europe and Canada may contribute to a decline in exposures to BPA also in Germany and Canada.

Government agencies in North America and the European Union [79–81], among others, have restricted the use of BPA in certain products because in animal studies, BPA can have reproductive and developmental effects [68]. Following such restrictions and the public pressure prompted from concerns regarding the toxicity of BPA and its potential adverse implications for human health, the use of BPA alternatives (e.g., other bisphenols, non-bisphenol products) may increase [68, 82–84]. However, information on the extent of exposure to

BPA alternatives is rather limited. Only one study so far has quantified concurrently BPA and three bisphenol analogs, bisphenol S (BPS, 4,4'-sulfonyldiphenol), bisphenol F (BPF, 4,4'-dihydroxydiphenylmethane), and bisphenol AF (BPAF, hexafluorobisphenol A), in samples collected between 2009 and 2012 from 100 US adults [85]. The highest frequency of detection and median concentrations were for BPA (95 %, 0.72 $\mu\text{g/L}$), followed by BPS (78 %, 0.13 $\mu\text{g/L}$), and BPF (55 %, 0.08 $\mu\text{g/L}$); BPAF was detected infrequently (~10 % of samples). These limited data suggest that US adults are exposed both to BPA and several bisphenol analogs. Future biomonitoring datasets using representative samples will be invaluable to track potential changes in human exposure to the alternative bisphenols from shifts in commercial formulations, public awareness, and regulations.

Pesticides: Organophosphate and Pyrethroid Insecticides

In the most recent market estimates of pesticide sales and use, insecticides were the second most common pesticide type, after herbicides, used in the USA in 2006–2007, and organophosphates constituted a significant portion of the insecticides used in US commercial and residential settings [86]. Nonetheless, of all insecticides used in the USA, the use of organophosphate insecticides has declined to 35 % in 2007 from 72 % in 2000. However, chlorpyrifos was the most commonly used organophosphate insecticide in 2007 despite the phasing out of chlorpyrifos from most home—including outdoor—uses and some agricultural applications in the early 2000s [87]. As a result, use of pyrethroids, labeled as less toxic than

organophosphates, for commercial and household residential applications has increased [88].

In population surveys, exposure to chlorpyrifos or chlorpyrifos-methyl has been generally assessed from the urinary concentrations of the specific metabolite 3,5,6-trichloro-2-pyridinol (TCPy), while 3-phenoxybenzoic acid (3-PBA), a non-specific metabolite of several pyrethroids, has been used as a biomarker of exposure to pyrethroid insecticides [19, 20, 30, 89]. Urinary concentrations of 3-PBA from GerES IV suggest that German children are exposed to synthetic pyrethroids [19, 20, 30, 89]. The lack of other survey data precludes the evaluation of trends of exposure to pyrethroids in Germany. By contrast, CHMS and NHANES data can be used to assess exposure trends to these insecticides in North America. For example, the median 3-PBA concentrations in CHMS participants 6–79 years of age increased from 0.22 µg/L (0.26 µg/g creatinine) in 2007–2009 to 0.36 µg/L (0.33 µg/g creatinine) in 2009–2011; CHMS does not include TCPy [30]. In NHANES, 3-PBA median concentrations have increased by 60 % from 0.25 µg/L in 1999–2000 to 0.40 µg/L in 2009–2010 [10]. Interestingly, the NHANES median concentrations of TCPy decreased by 39 % (1.70 vs 1.03 µg/L) during the same time period [10]. These results suggest a downward trend in exposure to chlorpyrifos and a parallel upward trend in exposure to its alternatives, synthetic pyrethroids, in the USA since the early 2000s. Although no data exist to track exposures to chlorpyrifos in Canada, based on CHMS biomonitoring data, exposure to synthetic pyrethroids seems to be on the rise.

Conclusion

The development and use of synthetic chemicals grew exponentially in the twentieth century to improve society's quality of life. These changes brought a parallel widespread exposure to many of these chemicals used in personal care and consumer products among all segments of the population in the USA and throughout the world. Because of the known animal toxicity of many of these chemicals (e.g., phthalates, BPA, organophosphate insecticides), increased public concerns, and government regulations, alternative chemicals are entering consumer markets. As a result, exposure to chemicals used in personal care and consumer products has changed in the past two decades. Understanding the extent of exposure to these chemicals is of public health relevance, and biomonitoring (i.e., measuring the concentrations of chemicals or their breakdown by-products in people) has been increasingly used as a tool for exposure assessment. Of interest, biomonitoring data also provide invaluable information to track exposure trends and show that although exposure to the original

personal care and consumer products chemicals is still prevalent among the general population, exposures to the alternative chemicals (e.g., non-phthalate plasticizers, other bisphenols, pyrethroid insecticides) appear to be on the rise, at least in the USA, Germany, and Canada.

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Compliance with Ethics Guidelines

Conflict of Interest Antonia M. Calafat, Liza Valentin-Blasini, and Xiaoyun Ye declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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