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Associations Between Flame Retardant Applications in Furniture Foam, House Dust Levels, and Residents' Serum Levels

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Abstract

Polyurethane foam (PUF) in upholstered furniture frequently is treated with flame retardant chemicals (FRs) to reduce its flammability and adhere to rigorous flammability standards. For decades, a commercial mixture of polybrominated diphenyl ethers (PBDEs) called PentaBDE was commonly applied to foam to fulfill these regulations; however, concerns over toxicity, bioaccumulation, and persistence led to a global phase-out in the mid-2000s. Although PentaBDE is still detected in older furniture, other FR compounds such as tris(1,3-dichloroisopropyl) phosphate (TDCIPP) and Firemaster® 550 (FM550) have been increasingly used as replacements. While biomonitoring studies suggest exposure is widespread, the primary sources of exposure are not clearly known. Here, we investigated the relationships between specific FR applications in furniture foam and human exposure. Paired samples of furniture foam, house dust and serum samples were collected from a cohort in North Carolina, USA and analyzed for FRs typically used in PUF. In general, the presence of a specific FR in the sofa of a home was associated with an increase in the concentration of that FR in house dust. For example, the presence of PentaBDE in sofas was associated with significantly higher levels of BDE-47, a major component of PentaBDE, in house dust (10^{β}=6.4, $p<0.001$). A similar association was observed with a component of FM550, 2-ethylhexyl-2,3,4,5-tetrabromobenzoate (EH-TBB), with levels that were approximately 3 times higher in house dust when FM550 was identified in the sofa foam ($p<0.01$). These

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Notes

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Associated Content

Supporting Information

Additional information on the structures and chemicals assessed (Table S1), abbreviations and components of mixtures analyzed (Table S2), and samples collected within the cohort study (Figure S1).

relationships were modified by dust loading rates in the living room and the ratio of sofa size to room size. Interestingly, levels of TDCIPP and tris(1-chloro-2-isopropyl) phosphate (TCIPP) were also higher in dust with detections in sofa foam; however, these associations were not statistically significant and may suggest there are other prominent sources of these compounds in the home. In addition, the presence of PentaBDE in sofa foam was associated with significantly higher levels of BDE-47 in serum ($p<0.01$). These results suggest that FR applications in sofas are likely major sources of exposure to these compounds in the home.

Keywords

Brominated flame retardants; polyurethane foam; house dust; exposure; serum biomarkers

Introduction

Flame retardants (FRs) are applied to polyurethane foam (PUF) in upholstered furniture to reduce its flammability. Implemented in 1975, the State of California's Technical Bulletin 117 (TB 117) mandated that all upholstered furniture pass a 12-second open flame test (State of California BEARHFTI, 2000). To pass these flammability tests, FR chemicals have been added to the PUF, and sometimes other components of furniture such as textile coverings. The polybrominated diphenyl ether (PBDE) commercial mixture known as PentaBDE was a common FR used in furniture foam; however, it was phased out in the mid-2000s. In response, organophosphate FRs such as tris(1,3-dichloroisopropyl)phosphate (TDCIPP), tris(1-chloro-2-propyl)phosphate (TCIPP), and the commercial FR mixture Firemaster® 550 (FM550), which contains triphenyl phosphate (TPHP), isopropylated triaryl phosphates (ITPs), 2-ethylhexyl-2,3,4,5-tetrabromobenzoate (EH-TBB) and bis(2-ethylhexyl)-tetrabromophthalate (BEH-TEBP), were increasingly applied as replacements (Stapleton et al., 2012b). In a recent study analyzing over one thousand foam samples collected between 2014 and 2016, TDCIPP was found to be the most common FR detected in furniture foam (Cooper et al., 2016). Despite the phase-out of PentaBDE and the recent amendment to TB 117 in 2013, which replaced the open flame test with a smolder test, flame retardants, including PentaBDE, are still detected in home furnishings and other foam-containing consumer products. This is due, in part, to slow product turnover and recycling of products themselves as well as the use of PUF in applications (Cooper et al., 2016; State of California BEARHFTI, 2013).

PBDE exposure and toxicity have been studied and characterized over the last few decades. The PBDE congeners associated with the PentaBDE mixture have been measured extensively in the environment and in human tissues, and exposure has been associated with negative impacts on thyroid hormone regulation and neurodevelopment, both in human and animal studies (Costa et al., 2014; Hale et al., 2003; Herbstman et al., 2010; Hites, 2004; Rahman et al., 2001; Zhou et al., 2002). Although less is known about other FRs, research conducted in the late 1970s suggested that TDCIPP is mutagenic, and more recently, that it may also be neurotoxic (Babich, 2006; Behl et al., 2016; Dishaw et al., 2011; Freudenthal and Henrich, 2000; Gold et al., 1978). Additionally, TDCIPP was added to California's Proposition 65 List of Possible Carcinogens in 2011. In contrast to PBDEs, TDCIPP is

rapidly metabolized and excreted. The metabolite, bis(1,3-dichloroisopropyl)phosphate (BDCIPP), has been measured ubiquitously in urine samples, suggesting widespread human exposure to TDCIPP in North America, Australia, and Europe; however, TDCIPP exposure appears to be higher in the U.S. population compared to other countries (Cequier et al., 2015b; Cooper et al., 2011; Dodson et al., 2014; Hoffman et al., 2017a; Van den Eede et al., 2015). Comparatively less is known about the toxicity of TCIPP, although it has been associated with endocrine disruption and limited neurodevelopmental changes in a few animal studies (Dishaw et al., 2014; Farhat et al., 2013). Like TDCIPP, exposure to TCIPP is also widespread. The hydroxylated metabolite of TCIPP has been ubiquitously detected in humans in several recent studies (Hammel et al., 2016; Van den Eede et al., 2015, 2013). Components of FM550 have been associated with endocrine and metabolic disruption in exposed rodents, and they have been shown to bind and activate nuclear receptors that regulate adipogenic pathways in *in vitro* models (Belcher et al., 2014; Fang et al., 2014; Patisaul et al., 2013; Pillai et al., 2014). Metabolites of both the organophosphate and brominated components of FM550, identified through dosed rodent studies and *in vitro* studies, are now frequently detected in human urine (Butt et al., 2016a, 2014; Hoffman et al., 2014; Phillips et al., 2016; Roberts et al., 2012). Notably, all of the aforementioned FR compounds have been widely detected in indoor house dust, which may serve as an important exposure pathway via hand-to-mouth activity (Bergh et al., 2011; Hoffman et al., 2015b; Stapleton et al., 2008; Van den Eede et al., 2012). In fact, several studies have found significant positive associations between PBDE levels in house dust and serum or breast milk in the US, reinforcing house dust as a primary exposure pathway (Johnson et al., 2010; Stapleton et al., 2012a; Watkins et al., 2012a; Wu et al., 2007). More recent studies have suggested that diet may play a larger role than dust for exposure to PBDEs, especially in European populations where PentaBDE was not used as pervasively in furniture as in North America. One recent study found no association between PBDEs in dust and serum but did find significant associations with various dietary items (Cequier et al., 2015a).

Despite these studies, research linking specific FR applications in products to house dust or biomarker levels is limited. Previously, portable x-ray fluorescence (XRF) measurements of bromine in products found in the home were shown to be highly correlated with Penta-BDE levels in paired house dust and serum samples (Allen et al., 2008; Imm et al., 2009). However, these portable XRF instruments are only sensitive to specific elements, such as bromine, and are not capable of differentiating between PBDEs or FM550, for example. Furthermore, XRF appears to have limited utility for chlorinated FRs (Stapleton et al., 2011). The presence of foam-containing napping equipment in early childhood education facilities also was associated with higher levels of tris(2-chloroethyl) phosphate (TCEP) and TDCIPP in dust (Bradman et al., 2014). A significant reduction in dust PBDE levels were observed with the removal of older furniture and carpets between sampling in 2006 and 2011; however, furniture was not verified to contain any specific FR chemicals, and the source of the reduction (e.g. furniture, dust-loading, or FRs in carpet padding) was not evaluated (Dodson et al., 2012). FR levels found on product surface wipes have been associated with dust levels; however, only prominent electronic products found in the home were evaluated, and most of the relationships were observed among these products and plastic casings, such as televisions and computers (Abbasi et al., 2016). In one study, counts

of baby products used in the home were correlated with urinary BDCIPP levels in infants, highlighting a possible link between product use and exposure (Hoffman et al., 2015a).

In the present study, we sought to further examine specific relationships between FR application in furniture foam and human exposure. Our goal was to identify and quantify specific FR applications in PUF from study participants' sofas in the main living area and determine how the presence or absence of a specific FR related to levels measured in house dust and residents' serum levels. Further, we sought to determine whether characteristics of the furniture or living space modified this relationship. To our knowledge, this is the first study to compare levels of specific FRs in a consumer product, particularly levels in upholstered furniture, to a known biomarker and to house dust.

Materials and Methods

Study Design

Participants were recruited as a part of a case-control thyroid cancer study between April 2014 and January 2016. Papillary thyroid cancer patients treated at the Duke Cancer Institute and Duke University Medical Center were invited to participate in the study by their physicians, and willing participants were contacted by our study team for enrollment (n=72). Control participants (n=81) were recruited via flyers in the Duke University Medical Center facilities or randomly selected as other Duke patients undergoing routine wellness care or care for unrelated illnesses. We assume that case status does not affect concentrations of flame retardants in furniture, dust or serum; hence, we included both cases and controls in the current study. The study population is described in greater detail in Hoffman *et al.* (2017b). Once enrolled, study personnel visited each participant's home to conduct questionnaires and collect environmental samples and biospecimens. The participants in the study all lived within 50 miles of Duke University and had lived in their homes for at least two years, ensuring that their current homes reflected several years of past exposure. On average, participants in this study lived in their homes approximately 11 years. All study protocols and related materials were approved by the Duke Medicine Institutional Review Board for Clinical Investigations, and all participants gave informed consent before providing any information or samples.

Sample Collection

All participants were instructed not to vacuum their homes in the two days before the visit. During each visit, the entire floor surface of main living area in the participant's home was vacuumed using a Eureka Mighty Mite vacuum fitted with a cellulose thimble in the hose attachment for dust collection (Stapleton et al., 2012a). The thimbles containing the dust were wrapped in aluminum foil and immediately frozen at −20°C. One small piece of foam (approximately 1–3 cm^3) was removed from the sofa located in the main living area, wrapped in foil, and immediately frozen. Almost all homes contained one sofa, but if other upholstered furniture (e.g. loveseats, chairs, ottomans, etc.) were present in the room, they were noted in the study log. Only PUF from the sofa, and not textile or fabric samples, were analyzed as part of this study. All participants provided non-fasting blood samples in serum-separator tubes which were centrifuged and frozen for analysis of PBDEs. Urine was not

collected as part of this protocol, and thus no biomarkers of organophosphate flame retardants were measured. Although all participants were asked to provide all samples, under some circumstances a particular sample could not be collected. For example, samples could not be collected from sofas that did not have accessible foam (e.g. leather sofas with no zippers to the cushion compartment). As such, there was not complete overlap in the number of participants with each sample type. Additional information on the sample sizes is included in the supplementary material (Figure S1).

Dust Extraction

Dust samples were extracted and analyzed similar to the methods developed by Van den Eede *et al.* (2012). In brief, dust samples (about 100 mg) were spiked with the following internal standards: d_{15}-tris(1,3-dichloro-2-propyl)phosphate (d_{15}-TDCIPP; 154.8 ng), ^{13}C-triphenyl phosphate (^{13}C-TPHP; 100.0 ng), ^{13}C-2-ethylhexyl-2,3,4,5-tetrabromobenzoate (^{13}C-EH-TBB; 100.0 ng), ^{13}C-bis(2-ethylhexyl)-tetrabromophthalate (^{13}C-BEH-TEBP; 100.0 ng), 4-fluoro-2,3,4,6-tetrabromodiphenylether (FBDE-69; 30.0 ng), and ^{13}C-decabromodiphenyl ether (13C-BDE209; 67.0 ng). The dust was extracted with 1:1 dichloromethane/hexane (v/v) via sonication extraction then concentrated to 1.0 mL using a nitrogen evaporator system. These extracts were purified using Florisil® solid-phase extraction cartridges (Supelclean ENVI-Florisil, 6 mL, 500 mg bed weight; Supelco), eluting the F1 fraction with 6 mL hexane (brominated compounds) and the F2 fraction with 10 mL ethyl acetate (PFRs). Each fraction was concentrated to 1 mL and then transferred to an autosampler vial for analysis by GC/MS. Recovery of the internal standards was assessed using ^{13}C labeled 2,2',3,4,5,5'-hexachlorodiphenyl ether (^{13}C-CDE141; 50 ng) for FBDE-69, d_9-tris(2-chloroethyl) phosphate (d_9-TCEP; 227 ng) for d_{15}-TDCIPP, and d_{15}-triphenyl phosphate (d_{15}-TPHP; 128 ng) for ^{13}C-TPHP. Recoveries of FBDE-69, ^{13}C-BDE-209, d_{15}-TDCIPP, and ^{13}C-TPHP were on average 109 ± 4%, 109 ± 7%, 90.6 ± 2%, and 79.6 ± 2%, respectively. Laboratory blanks and house dust standard reference materials (SRM 2585; National Institute of Standards and Technology, Gaithersburg, MD) were analyzed in each batch for quality assurance and quality control. Dust samples were analyzed in three separate batches, and MDLs were consistent across matches. Detection frequencies were determined based on the corresponding batch's MDL, and samples were blank-corrected by batch as well. Measurements of PBDEs in SRM 2585 were very similar to their certified levels, and ranged from 73 to 111% relative to the certified values. Levels of the FM550 components (TPHP, EH-TBB, BEH-TEBP) in SRM 2585 were 60–98% of the values reported in published literature (Ali et al., 2012; Van den Eede et al., 2012, 2011).

Foam Extraction

Foam samples were extracted and analyzed as in previously described methods (Stapleton et al., 2012b). Briefly, ~50 mg of foam was accurately weighed and extracted via sonication with dichloromethane (DCM) and then filtered with a 25 mm syringe filter with a 0.2 μm PTFE membrane. A 100 μL aliquot of each extract was removed and diluted to 1 mL for an initial screening of flame retardant additives by gas chromatography/mass spectrometry (GC/MS) in full scan using both electron ionization and electron capture negative chemical ionization. Three laboratory blanks (DCM with no foam) were analyzed with each batch of samples. Significant peaks in the total ion chromatogram were compared against a custom

spectral library of known FRs (Cooper et al., 2016). Based on the FRs identified in the scans, d_{15}-TDCIPP, ^{13}C-TPHP, ^{13}C-EH-TBB, ^{13}C-BEH-TEBP, and FBDE-69 were spiked into sample extracts for quantification by GC/MS. Due to the lack of standards at the time of analysis, the isopropylated triaryl phosphate (ITP) compounds were not quantified, but retention times and *m/z* ions were verified based on similarity with the FM550 mixture (Klosterhaus et al., 2009). The TBPP mixture (containing TPHP and mono-, di- and tri-tert-butylated phenyl phosphate esters) and MPP mixture (containing methyl phenyl phosphate esters) were similarly matched to a custom spectral library of FRs from previous characterization (Cooper et al., 2016; Stapleton et al., 2012b). It should be noted that FM550 was classified in this study by detection of EH-TBB and BEH-TEBP. Although typically associated with the ITP compounds, EH-TBB and BEH-TEBP were also observed in combination with the TBPP mixture (Cooper et al., 2016). Similar to dust, foam samples were analyzed in three separate batches, and detection frequencies were determined by each batch's MDL. MDLs were consistent across batches and therefore an average MDL was reported.

Serum Analysis

Serum was analyzed for PBDEs and extracted according to methods described in Butt *et al.* (2016). Briefly, the samples were spiked with 2.5 ng of FBDE-69 and ^{13}C-BDE-209. The samples were sonicated with 2.0 mL 0.1 M formic acid and 6.0 mL water to denature the serum proteins. Following column conditioning with 5.0 mL DCM, methanol, and water, the samples were loaded on a Waters Oasis® HLB column (500 mg bed weight, 6 mL) and washed with 5.0 mL water. PBDE analytes were eluted with 10.0 mL of 1:1 DCM/ethyl acetate (v/v), then concentrated to near dryness using a nitrogen evaporator and reconstituted in 1.0 mL hexane. These samples were further cleaned using a silica column cartridge (1 g, Waters, Sep-Pak), eluting the F1 fraction with 10.0 mL hexane for the PBDEs. The F1 fraction was concentrated to approximately 100 μL and spiked with 5.0 ng ^{13}C-CDE-141 to assess recovery of FBDE-69. This fraction was analyzed using GC/MS in electron capture negative chemical ionization mode for 27 PBDEs. Average recovery of FBDE-69 in the samples was 65 ± 2%. PBDE masses in serum were normalized to mass serum extracted as well as total lipid content. Serum triglycerides (TG) and total cholesterol (CHOL) were measured via enzymatic techniques (LabCorps, Burlington, NC). Total lipid content (TL) in serum was estimated using the equation reported by Covaci *et al.* (2006). Lab blanks and serum SRM 1957 (National Institute of Standards and Technology, Gaithersburg, MD) were extracted alongside the samples for quality assurance and quality control. The serum samples were analyzed in two separate batches, and detection frequencies as well as blank-correction was performed within each batch of samples. Measurements in SRM 1957 relative to the certified values were 129% for BDE-47 and 75% for BDE-153, and the range for all PBDEs measured in the SRM relative to certified values was 71 to 141%.

Product and Living Space Characteristics

To examine how product characteristics impacted analyzed relationships in this study, sofa footprint and dust-loading were defined based on measurements taken during home visits. The sofa footprint represents the sofa size relative to the size of a room, which allowed us to account for the amount of foam present in a main living space. This was calculated by

dividing the two-dimensional surface area of the sofa (length × width) by the surface area of the vacuumed main living space. Dichotomized at the median footprint, a small footprint represented sofas that took up <17.5% of the room, whereas a large footprint was indicative of a couch that took up >17.5% of the room. Dust-loading was determined by dividing the total mass of dust collected while vacuuming the main living space by the surface area of that room. Again, dichotomized at the median of 1.66 μg dust/in^2, low dust-loading is representative of lower dust masses collected from the surface area of the room, whereas high dust represented large masses of dust per area vacuumed.

Statistical Analyses

All analyses were conducted using SAS statistical software (version 9.4; SAS Institute Inc., Cary, NC). Analyses were performed for analytes detected in >70% of samples. Method detection limits (MDLs) were calculated by the standard deviation of the blanks multiplied by three and divided by the average mass of sample extracted. For all concentrations below the MDL, the concentration was replaced by MDL/2 (Antweiler and Taylor, 2008; Hornung and Reed, 1990). The FR concentrations in dust, foam, and serum were all log-normally distributed. For analyses, FR detections in foam were assessed as a dichotomized variable (FR present or absent in foam) due to the smaller sample sizes associated with each FR application. Positive identification of a FR in foam was determined as a concentration of at least 1 mg FR/g foam.

Linear regression models were performed to determine if FR presence in PUF and other variables were associated with dust or serum FR concentrations (log_{10}-transformed analyte concentrations used as outcomes). Beta coefficients were exponentiated to assist with interpreting the results and are representative of multiplicative change in the outcome relative to the reference category. Through all analyses, statistical results were assessed at a level of α=0.05 for significance.

Results and Discussion

Study Population

Overall, 153 participants were recruited for this study, and 115 provided a foam sample. Most of the study participants were female, and the mean age was 48 years. Further details about this cohort can be found in Hoffman *et al.*, 2017b. In brief, the cases and controls were similar in race and ethnicity, household income, and health history as well as average time reported living in the address at which the home visit was conducted (mean of 11 years).

FRs in Individual Matrices

Polyurethane Foam—Of the 115 foam samples collected, about two-thirds contained at least one flame retardant. The ITP mixture, which is associated with FM550 but also may be applied in other mixtures, was the most frequently detected flame retardant application (29% of total foam samples), followed by TDCIPP and then the brominated components (EH-TBB and BEH-TEBP) in FM550 (Table 1). Although it was the most frequently detected chemical in the foam samples (44%), TPHP is not typically applied on its own as a flame retardant. To our knowledge, TPHP is always co-applied with another flame retardant

mixture, such as with PentaBDE, or found with a mixture of phosphates as in the ITP mixture and the TBPP mixture. Therefore, while it is commonly detected, it is not the most frequently detected flame retardant application. The average FR levels in this study are similar to previously reported measurements in foam (Stapleton et al., 2012b). Penta-BDEs were still detected in over 15% of foam samples collected despite their voluntary phase-out in upholstered furniture occurring over a decade ago. While most of these particular sofas were reported as purchased prior to 2005, others were purchased second-hand or handed down; therefore, the original manufacturer and purchase date is unknown. Concentrations of FRs in foam reported in Table 1 are for individual FRs; however, many of these FRs are applied as mixtures. Generally, the total concentration of all FRs applied to the foam were >1% of the product by weight.

Serum—Serum samples were analyzed for a suite of PBDE compounds but only BDE-47 and BDE-153 were detected in >70% of the samples and are the only congeners analyzed in this study for associations with FR applications in foam (other congeners were detected in under 50% of samples) (Table 2). More information on the serum PBDE measurements can be found in Hoffman *et al.* 2017b. In general, the levels of these two compounds were lower than previously reported among U.S. adults, which likely reflects a decline in overall exposure to Penta-BDEs following their phase-out (Buttke et al., 2013; Sjödin et al., 2008). While such a decrease is expected with a now decade-old global phase-out of Penta-BDEs, detection of these two BDEs in serum suggests continued exposure to these compounds.

House Dust—Of the FRs quantified in foam, all were detected in 70% or more of the dust samples (Table 2). Overall, the geometric means of organophosphate FRs in dust were at least an order of magnitude greater than the brominated compounds, which suggests greater exposure potential for organophosphate compounds via dust ingestion. The most abundant organophosphate FR in dust was TCIPP, which follows a trend observed in the U.S. and parts of Europe and Asia (Araki et al., 2014; Brommer and Harrad, 2015; Cequier et al., 2014; Dodson et al., 2014; Stapleton et al., 2014). Although PBDEs have been largely phased out, detections and concentrations of the more widely used PBDEs (BDE-47 and BDE-99 in PentaBDE and BDE-209 of the DecaBDE mixture) in dust were similar to the levels of the other brominated compounds, EH-TBB and BEH-TEBP. This suggests that despite decreased use, house dust serves as a continued repository for PBDEs, and sources of PBDEs may still be present in homes.

Comparing PBDEs in Foam and Serum

Levels of serum BDE-47 and BDE-153 were greater in participants who lived in a home with a sofa containing Penta-BDEs (Figure 1). Serum BDE-47 levels were 2.5 times as high in these participants compared to those whose sofa did not contain Penta-BDE (95% CI: 1.4, 4.5; $p<0.01$). Although not statistically significant, a similar pattern was observed for serum BDE-153 levels, with BDE-153 in serum being about 1.7 times as high if the participants had a Penta-BDE-containing sofa (95% CI: 0.84, 3.3; $p=0.14$). The lack of a significant association between BDE-153 in serum and Penta-BDE in foam may be due to a difference in the half-lives of BDE-153 compared to BDE-47, or differences in exposure. Additionally, diet may be a greater source of exposure for BDE-153 in the present day than it did prior to

the global phase-out due to its persistence in the environment. BDE-47 has been estimated to have a half-life of 1.8 years, while BDE-153's half-life has been estimated to be 6.5 years (Geyer et al., 2004). Therefore, BDE-153 measured in serum would likely reflect longer-term average exposures from either past furniture containing Penta-BDE or other sources present in the last several years of the participants' exposure, which could include diet or other microenvironments (Watkins et al., 2012b). Additionally, the relationship between Penta-BDE in sofa foam and BDE-47 in serum was slightly stronger if individuals spent an average of 13 hours or more in their homes per day (10^{β}=2.8, p=0.01) compared to people who did not have Penta-BDE in their sofas. Furthermore, BDE-47 in dust was significantly correlated with paired BDE-47 serum levels in this cohort (r_s=0.35, p=0.004) but a similar relationship between dust and serum was not observed for BDE-153 (Hoffman et al., 2017b). Past studies have shown significant associations between serum and house dust for certain PBDEs (r_s=0.8 for BDE-47 in adults, r=0.3 for a summed BDE-47, −99, and −100 in toddlers; p<0.01), but not for BDE-153 (Johnson et al., 2010; Stapleton et al., 2012a). To our knowledge, serum PBDE levels have not been previously linked to a specific application in a product. The significant association between foam Penta-BDE and serum BDE-47 suggests that these pieces of upholstered furniture serve as major sources of BDE-47 in humans. Because there are no other reliable serum biomarkers for the additional FRs investigated here, only relationships with PentaBDE were investigated with serum.

FRs in Foam and Dust

The presence of FM550 and Penta-BDEs in the sofa foam were significantly associated with higher levels of EH-TBB and BDE-47 in dust, respectively (Figure 2). The EH-TBB and BDE-47 dust levels were between 4 to 6.5 times as high when a sofa containing that specific FR was in the same living area (FM550 95% CI: 1.7, 9.8; PentaBDE 95% CI: 2.8, 14.3; p<0.01). While sofas may not be the sole source of FRs, associations indicate that foam-containing furniture contributes heavily to house dust and serves as a major source of brominated FRs in house dust. This implies that having a sofa that does not contain either of these brominated FR mixtures could potentially decrease a person's exposure to these compounds via decreases in FR levels in dust. The magnitude of effect between Penta-BDE detection in foam and BDE-47 dust levels was much greater than the effect with BDE-47 in serum (6.5 times in dust compared to 2.5 in serum), which suggests that the relationship observed between foam and serum is attenuated, perhaps by the time spent in other micro-environments (e.g. home, work), handwashing, and/or dietary sources, even if the sofa may serve as a major source of exposure (Watkins et al., 2012b). Relationships between dust levels of other PBDEs (BDE-99, −100, −153, −154) were evaluated with Penta-BDE in foam and were found to be significantly associated (10^{β}=3.2–3.9, p<0.01) with one exception being BDE-153 (10^{β}=2.2; p=0.07). Dust levels of BEH-TEBP were also assessed with FM550 presence in foam and were found to be statistically significant (10^{β}=3.8, 95% CI: 1.3, 11.2, p<0.01). Because BDE-47 and EH-TBB showed the strongest relationship with their respective applications in foam, and BEH-TEBP may be applied in other commercial mixtures in the home, the results with BDE-47 and EH-TBB are presented in the figures and further evaluated with other characteristics.

The relationships between foam and dust were investigated further based on various product characteristics and living space traits. When the Penta-BDE relationship between foam and dust was assessed based on the sofa footprint, levels of BDE-47 in dust were found to be 9.7 times as high when the sofa had a large footprint compared to only 4.3 times as high with a small footprint (large footprint 95% CI: 3.0, 31.8; small footprint 95% CI: 1.6, 11.3; $p<0.01$; Figure 3), relative to dust levels in homes without a Penta-BDE sofa. A similar trend was observed with FM550 and EH-TBB in dust (large footprint $10^{\beta}=4.5$, 95% CI: 1.5, 13.3; small footprint $10^{\beta}=7.6$, 95% CI: 1.5, 39.8; $p<0.05$), although the sample sizes for each category were small, resulting in overlapping confidence intervals in the small and large footprint categories. Overall, the trend suggests that sofas that take up more of the surface area of the room contribute to higher levels of these brominated FRs in dust.

Dust-loading of the vacuumed room was also examined as a potential modifying factor in the foam-dust relationship. When compared to the reference category (low dust mass loadings and no Penta-BDE in foam), a significant relationship between Penta-BDE in foam and BDE-47 levels in dust was observed with low dust-loading ($10^{\beta}=10.4$; 95% CI: 3.5, 31.1; $p<0.0001$; Figure 4). A significant relationship was not observed with high dust-loading levels, although the results were suggestive of a trend ($10^{\beta}=2.8$; 95% CI: 0.9, 8.2; $p=0.07$). Again, the same trend was observed with FM550 in foam and EH-TBB in dust (low dust $10^{\beta}=6.5$; 95% CI: 1.8, 22.8; high dust $10^{\beta}=4.3$; 95% CI: 1.2, 15.1; $p<0.05$), but sample sizes were not sufficiently large, resulting in overlapping confidence intervals. This finding may suggest that a dilution effect is occurring, whereby the brominated compounds are diluted in a room that accumulates more soil or dust particles (leading to higher dust mass in a room). Therefore, dust-loading may be an important variable to consider when assessing relationships between product use and house dust levels, as it could modify the observed relationships and lead to incorrect estimates.

As for the organophosphate FRs, higher levels of TCIPP and TDCIPP in dust were observed when detected in the sofa foam; however, the relationships were not statistically significant ($10^{\beta}=1.6–2.5$, $p>0.1$; Figure 2). Interestingly, when TCIPP and TDCIPP were not detected in the sofa foam, the GM dust levels of these two organophosphate compounds were an order of magnitude greater than EH-TBB and BDE-47. This suggests that product sources other than sofas in the main living area may be contributing to the dust concentrations of these two organophosphate FRs, or TCIPP and TDCIPP may have different migration behaviors than the brominated compounds from foam to dust due to physicochemical properties. However, the upholstered furniture seems to be a major source of FM550 and Penta-BDE in the home. TDCIPP and TCIPP relationships between foam and dust were assessed based on footprint and dust-loading but no associations were observed, further suggesting that sofa foam assessed in this study may not be the main source of these organophosphates in dust. For instance, TCIPP is frequently used in thermal insulation, and both of these organophosphates could be used in a variety of applications in textiles (Andresen et al., 2004; Ionas et al., 2015; van der Veen and de Boer, 2012).

Limitations

Although participants in this study were recruited for the purpose of a case-control study to examine thyroid cancer, this should not bear any effects on this particular study since case status should not impact foam, dust, or serum levels of FRs. As shown in Hoffman *et al.* 2017b, there was no significant difference in serum BDE-47 or BDE-153 levels by case status. Still, our results should be interpreted in the context of a few limitations. First, one foam sample was assessed per household for associations with house dust; this does not account for the possible contribution of other upholstered furniture in the room or adjacent rooms. Due to different applications of FRs in foam, the sample sizes of foam samples containing a specific FR were relatively small compared to those that did not. As a result, relationships between foam and dust were assessed based on detection (>1 mg/g foam) rather than on a continuous basis. Detailed behavioral information such as how much time an individual spent in the main living area or on the sampled sofa and frequency of handwashing could provide additional insights, as these factors could modify the relationship between foam and human exposure. Future studies including analyses with urine measurements from participants may also be helpful to determine how organophosphates assessed in foam relate to biomarkers for exposure.

Conclusion

Our results indicate that foam in sofas serves as an important source of flame retardants for exposure in humans, suggesting that removal of FRs from the foam or furniture pieces in the home could indeed reduce human exposure to these compounds. FR compounds were measured in foam samples and evaluated for their associations with paired serum and house dust samples. Significantly higher levels of serum BDE-47 were observed when the participant had a sofa containing Penta-BDE in the main living area with a similar but non-significant relationship observed with serum BDE-153. Detections of FM550 and Penta-BDE in foam were also indicative of significantly greater levels of EH-TBB and BDE-47 in dust, suggesting that foam in upholstered furniture containing these brominated mixtures serves as a major source of these compounds in the home environment. These relationships were strengthened with larger furniture pieces per area vacuumed (sofa footprint) and with lower dust-loading. Foam-dust relationships were not significant for TDCIPP or TCIPP, suggesting that other sources of these two compounds may be contributing to the levels measured in house dust or the compounds migrate from foam to dust in a manner different from the brominated compounds.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

- PentaBDE and FM550 in foam is associated with higher levels in dust.
- Foam-dust associations were not observed for TDCIPP and TCIPP.
- Sofa footprint in the living area and dust loading rates modified associations.
- PentaBDE in foam was significantly associated with higher BDE-47 in serum.

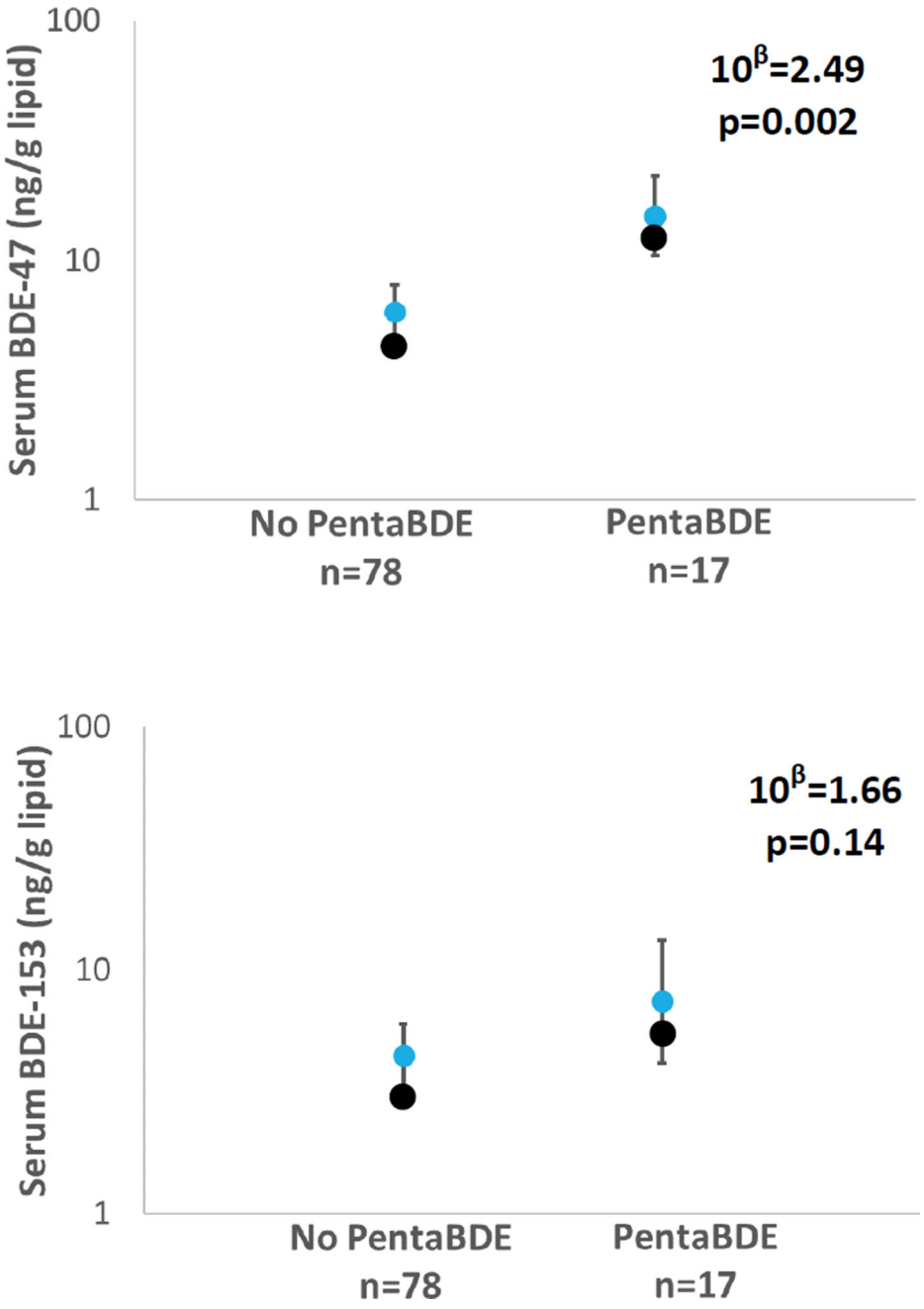

Figure 1.

Geometric means and 95% confidence intervals of serum PBDE levels based on presence or absence of PentaBDE in paired foam. Absence of PentaBDE in foam was the reference category for determining the magnitude of effect on serum BDE-47 and BDE-153, which was determined by linear regression.

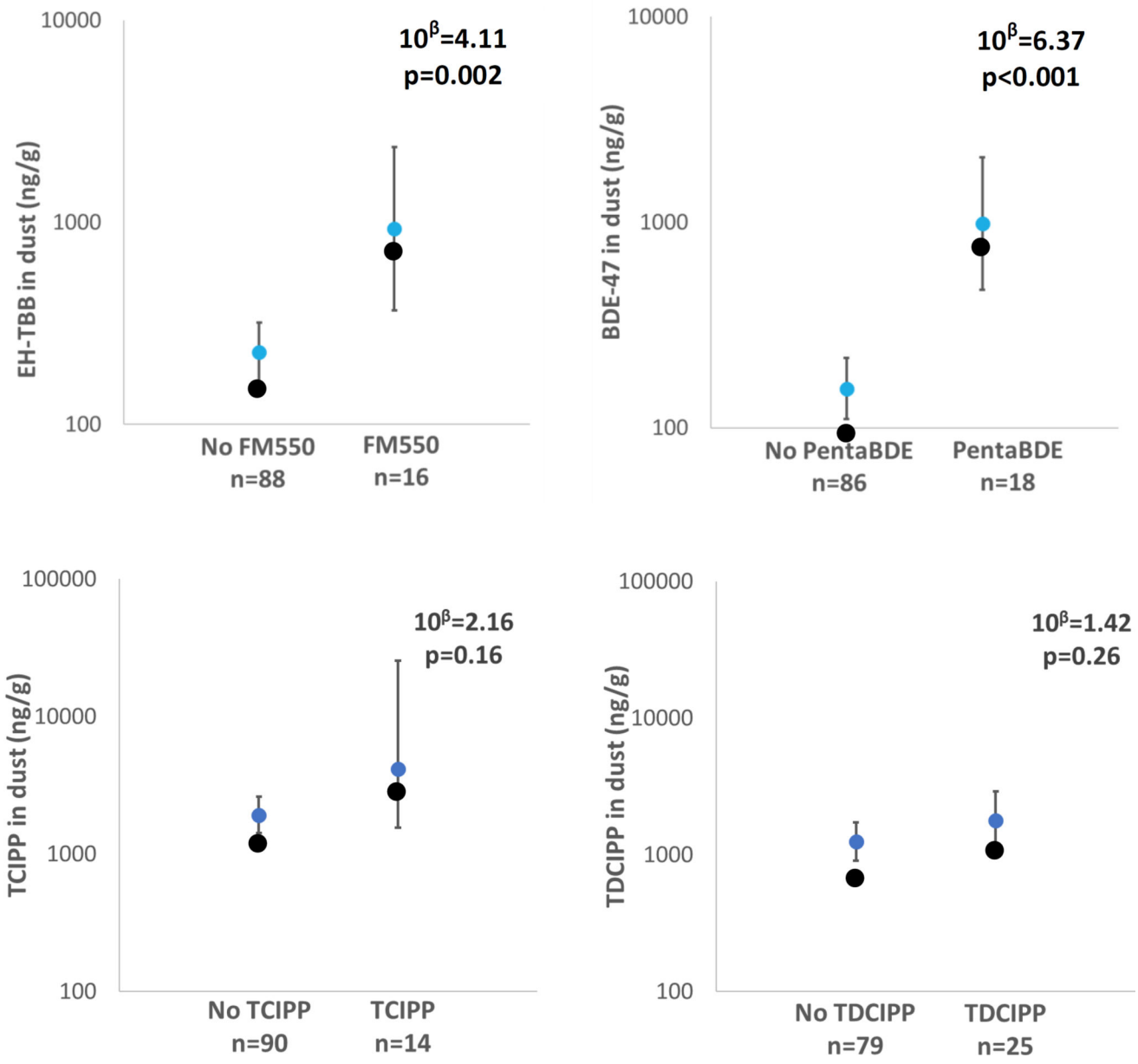

Figure 2.

Geometric means and 95% confidence intervals of dust concentrations based on the corresponding FR's presence or absence in paired foam. The magnitude of increase in outcome and associated p-value with the FR foam presence compared to absence (reference category) are displayed in the top right of each panel, which was assessed by linear regression.

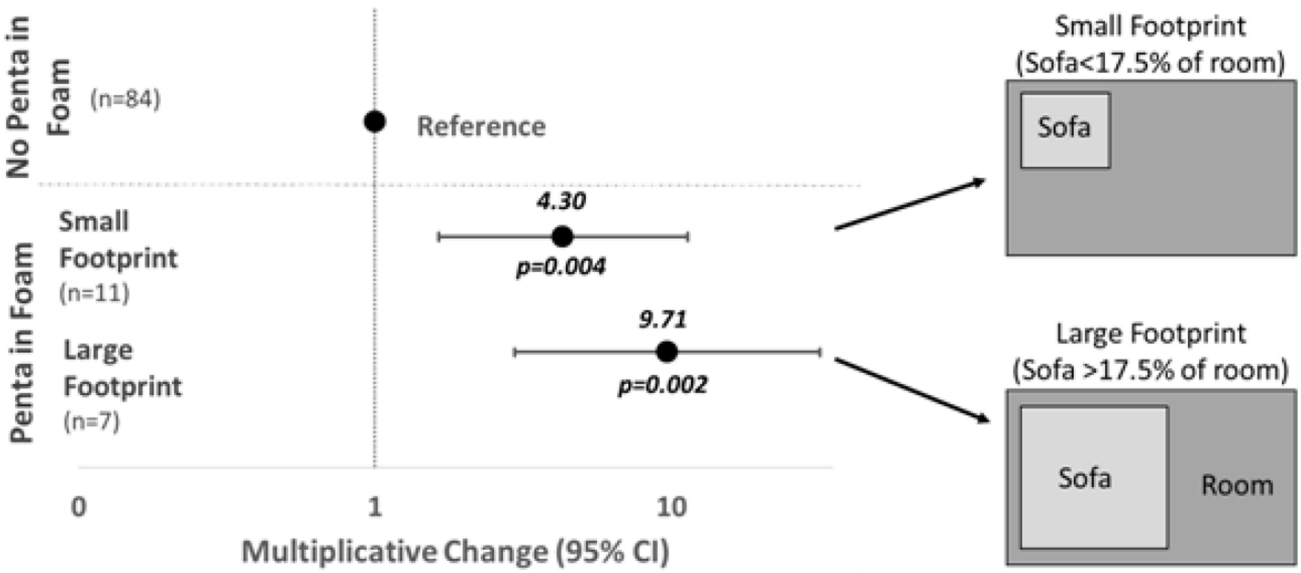

Figure 3.

Multiplicative change and 95% confidence intervals of BDE-47 in dust depending on the presence of PentaBDE in paired foam and the size of the sofa relative to the vacuumed room, designated as a footprint. The sofa footprint was dichotomized at the median percent of the room covered by the sofa (17.5%).

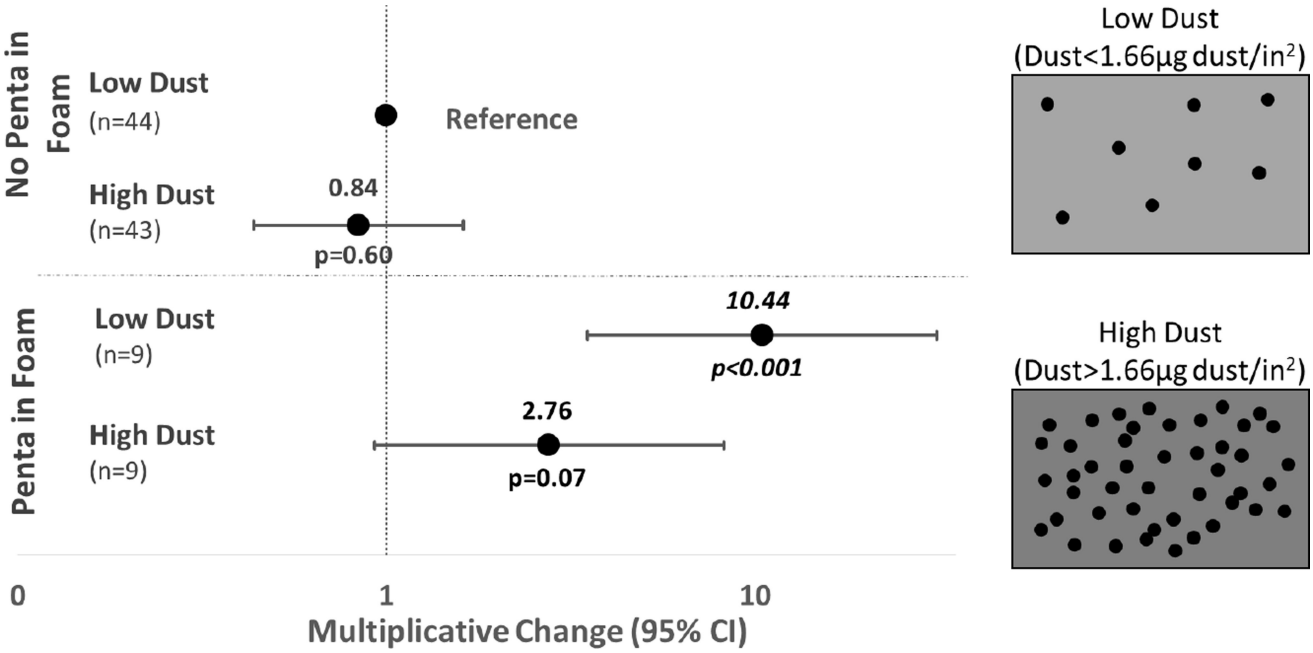

Figure 4.

Multiplicative change and 95% confidence intervals of BDE-47 in dust depending on the presence of PentaBDE in paired foam and dust-loading of the vacuumed room. Dust-loading was dichotomized at the median dust mass per area vacuumed, which was 1.66 μg/in^2.

Table 1

Detections, geometric means, and ranges (mg/g foam) for flame retardants in polyurethane foam samples (n = 115).

Compound	Number of Detects	% Detect of Total Samples	Average MDL	Geometric Mean	Minimum	Maximum
EH-TBB	20	17.4	0.227	8.79	1.97	15.9
BEH-TEBP	20	17.4	0.341	3.91	0.514	7.54
ΣPentaBDE *	18	15.6	0.055	3.74	0.941	35.0
TCIPP	7	6.08	0.261	6.32	0.768	46.0
TDCIPP	22	19.1	0.236	19.9	0.534	88.1
TPHP	51	44.3	0.124	0.983	0.0013	15.0
ITP Compounds#	33	28.7	n.a.	n.a.	n.a.	n.a.
TBPP Compounds%	14	12.2	n.a.	n.a.	n.a.	n.a.
MPP Mixture&	4	3.47	n.a.	n.a.	n.a.	n.a.
No FR	37	32.2	n.a.	n.a.	n.a.	n.a.

*ΣPenta-BDEs includes BDE-17, 28, 47, 49, 66, 85, 99, 100, 153, 154, and 155.

#ITP compounds refer to a mixture of isopropylated triaryl phosphate esters.

%TBPP compounds refer to a mixture of tert-butylated phenyl phosphate esters.

&MPP Mixture refers to a mix of methyl phenyl phosphate esters.

Table 2

Geometric means and selected percentiles for FRS in serum (n = 135) and house dust (n = 137).

				Percentile			
Matrix and Compound	**Percent Detect**	**Average MDL**	**Geometric Mean**	**25th**	**50th**	**75th**	**Maximum**
Serum (ng/g lipid)							
BDE-47	77.8	1.321	7.855	3.852	8.891	16.01	144.2
BDE-153	94.8	0.5490	4.541	2.386	4.371	8.576	143.2
Dust (ng/g dust)							
EH-TBB	94.2	3.833	239.4	82.86	188.4	754.4	16,320
BEH-TEBP	81.8	15.60	117.1	44.67	160.4	420.6	11,190
TCIPP	94.2	90.90	2,141	823.5	2,118	6,350	66,210
TDCIPP	92.0	56.97	1,384	640.7	1,220	3,269	59,490
TPHP	95.6	5.000	1,409	475.5	1,345	4,049	111,300
PBDEs							
BDE-47	92.0	78.50	222.2	71.65	202.2	518.5	17,010
BDE-99	96.4	74.30	346.1	100.3	310.4	789.7	32,820
BDE-100	70.1	20.70	62.51	18.35	44.38	155.0	6,396
BDE-153	87.6	10.37	43.99	11.90	34.49	124.5	4,488
BDE-154	81.8	8.100	31.88	9.067	27.27	77.79	3,657
BDE-209	93.4	20.13	524.1	184.2	536.9	1198	28,490