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A Newly Recognized Occupational Hazard for US Electronic Recycling Facility Workers: Polybrominated Diphenyl Ethers

Arnold Schecter, MD, MPH
Justin A. Colacino, BS
T. Robert Harris, PhD
Nirav Shah, MBBS
Sharon I. Brummitt, BA

Learning Objectives

- Review the industrial uses, biologic effects, and evidence for health risks of polybrominated diphenyl ethers (PBDEs), including the current use of commercially marketed PBDE mixtures.
- Analyze previous data on PBDE exposure in occupational and environmental settings, including past studies in electronic recycling facilities.
- Summarize the new estimates of PBDE exposure among electronic recycling facility workers, along with the recommendations for monitoring and protection of exposed workers.

Abstract

Objective: *To describe a newly recognized US occupational health hazard, polybrominated diphenyl ether (PBDE) flame retardant exposure, to US workers at electronics recycling facilities to communicate this information to occupational medicine physicians and related health workers.* ***Methods:*** *Using PBDE air values reported from a California electronic recycling facility and estimates of US food, air and dust intake, electronic recycling facility workers' PBDE exposure at this facility was estimated using multiple possible scenarios. We compared these estimates to intake estimates for the US general population. Occupational PBDE study findings from China, Sweden, and Norway where elevated environmental or blood PBDE levels were detected in similar workers are reviewed.* ***Results:*** *An approximate 6-fold to 33-fold increase in the electronic recycling facility workers' PBDE exposure was estimated compared with the US general population.* ***Conclusion:*** *PBDE exposure in US electronic recycling facilities is a largely unrecognized occupational health hazard. The extent of worker exposure in the US should be better characterized and steps taken to lower levels of PBDEs in the workplace where exposure exists. Health care providers, plant safety professionals, and government agencies can play a role in recognizing the problem and in decreasing worker exposure.* (J Occup Environ Med. *2009;51:000–000*)

From the Division of Environmental and Occupational Health Sciences, Division of Epidemiology, University of Texas School of Public Health at Southwestern Medical Center, Dallas, Tex.

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Address correspondence to: Arnold Schecter, MD, MPH, University of Texas School of Public Health at Dallas, 5323 Harry Hines, V8.112, Dallas, TX 75390-9128; E-mail: arnold.schecter@utsouthwestern.edu.

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Polybrominated diphenyl ethers (PBDEs) are a class of chemicals which have been widely produced and used since the 1970s as additive flame retardants in many consumer products, such as carpet linings, mattresses, polyurethane foam used in sofas and chairs and the hard plastic casing used for televisions and computers.[1,2] They are lipid soluble, persistent, toxic chemicals that bioaccumulate in humans. PBDEs are commonly used because of their low cost and resistance to degradation by biological, physical, and chemical processes.[3] There are 209 different PBDE congeners. Thirteen congeners are usually found in the three commercially marketed mixtures. These mixtures, named according to the average number of bromines in the molecules, are called pentabrominated diphenyl ether (Penta-BDE), octabrominated diphenyl ether (Octa-BDE), and decabrominated diphenyl ether (Deca-BDE).[2] Today, both Penta-BDE and Octa-BDE have been banned in Europe and are being voluntarily phased out in the United States.[4] The Deca-BDE mixture was banned by the European Court of Justice but continues to be produced and used in high volumes today in the United States; however, two states, Maine and Washington, have enacted bans on certain uses of Deca-BDE, such as in mattresses and in some upholstered furniture.[5]

PBDE exposure can occur through food intake as well as for dust and air through dermal absorption and inhalation.[6–8] PBDE levels in blood and

TABLE 1
Total Blood PBDE Levels (ng/g) in Electronic Recyclers and Reference Groups in Different Countries

		Total Blood PBDE Levels (Median, ng/g)					
		Electronic Recyclers		Reference Group A		Reference Group B	
Study	Country	ng/g	*n*	ng/g	*n*	ng/g	*N*
Sjodin et al[7]*	Sweden	26	19	Hospital cleaners 3.3	20	Computer clerks 4.1	20
Thuresson et al[33]†	Sweden	26.8	8	White collar workers 11.8	6	NA NA	
Qu et al[34]‡	China	126	20	Residents from nearby region 35	15	General population 10.4	20
Bi et al[24]§	China	600	26	Residents from nearby region 170	21	NA	
Thomsen et al[35]‖	Norway	8.8 (Mean)	5	Circuit board producers 3.9 (Mean)	5	Laboratory personnel 3 (Mean)	5

*BDE 47, 77, 85, 99, 100, 128, 138, 153, 154, 183, 209.
†BDE 47, 99, 100, 153, 183, 209.
‡BDE 28, 47, 99, 100, 153, 154, 183, 196, 197, 203, 206, 207, 208, 209.
§Total 16 congeners were identified including BDE 153, 183, 196, 197, 203, 206, 207, 208, 209.
‖BDE 28, 47, 99, 100, 153, 154, 183.
n indicates Number of persons; NA, not applicable.

milk in the population of the United States have been found to be 10 to 100 times higher than in European populations.[9–11] The rapidly increasing level of PBDE exposure during the past few decades constitutes a risk to human health.[12] Animal studies suggest that PBDEs cause health defects including cancer at high dose levels,[13] delayed onset of puberty,[14] decreased sperm count,[15] fetal malformations,[16] endocrine disruption,[17] permanent learning and memory impairment[18] and behavioral changes.[19,20] Recent studies involving humans suggest that elevated levels of PBDEs in breast milk are associated with cryptorchidism in newborn boys[21] and adverse birth outcomes, particularly low birth weight and decreased length and chest circumference of infants.[22] One other recent human study also noted an inverse correlation between serum PBDE levels and sperm count in young men.[23] Occupational PBDE exposure has been shown to occur in various settings in other countries.[24–26] Occupational exposure can occur in a number of settings including PBDE manufacturing plants; facilities where PBDE-containing products, such as polyurethane foam or electronics, are manufactured, repaired or recycled; in office settings where workers spend a large amount of time near computers or other electronics; and during the process of carpet installation or removal.[25–28] A recent study also reported elevated PBDE blood levels in Nicaraguan children working informally as scrap scavengers at a large municipal solid waste disposal site.[29] Children living near and working at the waste site had measured blood levels 20 to 50 times higher than the reference group, children from urban Managua, Nicaragua.[29]

Methods of assessing occupational PBDE exposure include monitoring PBDE levels in the air and dust from the workplace and surrounding areas. These measurements can be susceptible to seasonal variation and are sensitive to equipment being brought in or removed from the work environment.[30] The current gold standard for PBDE exposure assessment is biomonitoring, or estimating the body burden by sampling blood from potentially exposed workers to measure PBDE congener elevation.[31] In the case of PBDE exposure, biomonitoring cannot necessarily determine the source or the route of exposure, because exposure can occur in many settings including home, car, and workplace.[32] However, biomonitoring studies are useful for identifying and characterizing worker exposure and can indicate the need for improved worker safety measures.[28]

Biomonitoring studies in Europe and China have already established that electronic recycling facility workers can have increased PBDE body burdens when compared with reference groups, as indicated by blood levels. As shown in Table 1, total blood levels (sum of all measured congeners) were measured in electronic recycling facility workers from three different countries, Sweden, China, and Norway. The median total levels in workers ranged from 26 ng/g lipid in Sweden to 600 ng/g lipid in China. The Swedish study showed the median total PBDE blood levels in electronic recycling facility workers was seven times higher than the reference group which consisted of hospital workers and computer clerks.[7] Another study published in Sweden found that electronic recycling facility workers had total PBDE blood levels approximately twice as high as the reference group of office workers who worked at the same recycling plant.[33]

Table 1 also shows a study from China with measured median values of total PBDE blood levels in electronic recycling facility workers that were 3.6 times higher than residents living approximately 50 km from the electronic recycling facility, and 12 times higher than a group of people living in another city of China with no known exposure to PBDEs.[34] A study from Guiya, China, also seen in Table 1, described the median total PBDE blood levels in electronic recycling facility workers to be 3.5 times higher than the residents in a nearby region (50 km away from the electronic recycling facility plant).[24] In Norway, electronic recycling facility workers had total mean PBDE blood levels 2 to 3 times higher than a reference group of circuit board producers and laboratory personnel.[35] Each study measured a different group of congeners, as listed in Table 1, which leads to some uncertainty as to the actual total PBDE levels in these studies and limits the comparisons that can be drawn between studies.

Electronic or foam recyclers and carpet installers have been shown previously to have higher levels of PBDE exposure than the general population and therefore could be at increased risk for adverse health consequences.[28] A major goal of this article involves comparison of occupational PBDE exposure of US electronic recycling facility workers with the US general population and communication of these findings to occupational medicine physicians and related health workers.

Materials and Methods

The California Air Resource Board (CARB) measured PBDE levels in indoor air at a California electronic recycling facility.[36,37]

Exposure Estimate

Total PBDE exposure for the general population and workers was calculated as the sum of the PBDE exposure from air inhalation and food ingestion and dust or soil intake. Air and dust exposure were calculated as a time weighted average of the total PBDE levels found in air or dust in four locations—home, work, outdoors, and in automobiles—multiplied by either total air inhalation or dust intake. Estimated total PBDE exposure from food was calculated previously and summarized here.[8]

Scenario Analyses

Our estimate of total PBDE intake is based on combining estimates of quantity of food, air and dust, or soil exposure with estimates of total PBDE levels in food, air and dust, or soil in various settings. Information about these components comes from a variety of sources. In some cases, the information is very limited or uncertain; in these cases, we make a range of different assumptions. Four parts of the model were identified where lack or sparsity of applicable data could potentially have a large effect on the final outcome: PBDE levels in car dust, PBDE levels in car air, dust intake by the electronic recycling facility workers, and PBDE levels in the dust at the electronic recycling facility. Combining the alternate assumptions for these components in all possible ways led to 24 different scenarios, each with its own estimate of total PBDE intake. The goal of the multiple scenario approach was to create a window in which the true, but currently unknown, PBDE exposure levels exist. Ratios of estimated total PBDE exposure in the electronic recycling facility workers to the general population were calculated. Computations for each scenario used SAS software version 9.1 (Cary, NC).

Food Exposure

We assume in our exposure estimates that the body mass for a worker in the electronic recycling facility was the same for an individual in the general population and was estimated in the model as the average of the mean weight of adult men (86.1 kg) and adult women (74.0 kg) from recent US survey data (NHANES) for an overall estimate of 80 kg.[38] Previously published research was used for our calculation of US adult PBDE exposure from food (approximately 1.0 ng/kg body weight/d)[8] based upon the assumption that there is no difference in food consumption between US exposed workers and the US general population. Therefore, for an average adult with a weight of 80 kg, the estimated total PBDE intake (the sum of all measured PBDE congeners) from food is approximately 80 ng/d.

Dust Exposure

Exposure to PBDEs via dust was calculated by multiplying the total amount of dust intake per day by the mean PBDE level in dust. The daily dust intake for the general population was estimated to be 50 mg/d, using the EPA central dust intake estimate.[39] Because, in the California electronic recycling facility, no personal protective equipment was in use, it is possible that facility workers ingested more dust than individuals in the general population.[36,37] Therefore, we used two different estimates of the dust intake of the electronic recycling facility workers. The first estimate assumes the dust intake is the same as the general population, 50 mg/d.[39] The second estimate assumes increased dust intake for the electronic recycling facility workers, and uses the EPA high dust intake estimate, 100 mg/d.[39]

The mean PBDE level in dust was calculated as a time weighted average of levels in homes, in workplaces, in automobiles, and outdoors. Weights are based on estimates from the EPA Exposure Factors Handbook, which estimates that 53% of an average adult's time is spent at home, 33% is spent at work, 7% is spent in an automobile, and 7% is spent outdoors.[39] PBDE level in dust at home is based on the combined data from two studies conducted by the same research group resulting in a relatively large sample size and a median total PBDE level in US house dust to be 6503 ng/g.[40,41] The levels in household dust are assumed to be similar for electronic recycling facility workers and the general population for the purposes of this model. PBDE level in dust at work for the general population was estimated as the median total PBDE level in US house dust, 6503 ng/g, as no published research for occupational dust levels in the US exists.[40,41] For the PBDE level in dust in the electronic recycling facility, we made two different assumptions to deal with the uncertainty in the data. First, we estimate the PBDE level in dust at the electronic recycling facility as the median level found in US homes, 6503 ng/g.[40,41] Alternatively, we estimate the PBDE level as the highest value from previously published US house dust, 269,200 ng/g.[40,41] The PBDE levels in dust in the electronic recycling facility could be considerably elevated judging from the elevated levels of PBDEs found in the air at the facility.[36,37] PBDE levels in automobiles were estimated in two ways, as only one published article from the UK has measured PBDE levels in automobile dust.[42] The first estimates the total level as the lowest measured in the study, 140 ng/g.[42] The second estimate uses the median total PBDE level from the same study, 57,000 ng/g, an already elevated level.[42] PBDE levels in outdoor dust or soil were estimated by the geometric mean from the only published research on PBDE levels in soil from various geographic locations in the US, 5.3 ng/g.[43]

Air Exposure

Exposure to PBDEs through air was calculated by multiplying the total amount of air intake per day by the mean PBDE level in air. The daily air intake for an average adult was estimated to be 13.25 m^3/d, using the EPA Exposure Factors Handbook.[39]

The mean PBDE level in air was calculated as a time weighted average of levels in homes, in workplaces, in automobiles, and outdoors. The weights used are the same as in the dust exposure above.[39] PBDE levels in air at home were estimated from values taken in the largest US indoor air study to date of PBDEs, which found a median total PBDE concentration of 472 pg/m^3.[44] PBDE levels in air at work for the general population were estimated using the same value, 472 pg/ m^3, as few published reports exist for PBDEs in US workplace indoor air. PBDE levels in air at work for the electronic recycling facility workers were estimated using measurements by the CARB that found a mean total PBDE level of 650,000 pg/m^3.[36,37] PBDE levels in air in automobiles was estimated in three different ways, all using data from a recent European study measuring the total PBDE air levels in 33 automobiles manufactured in the US, Europe, and Japan.[45] The alternative estimates were created to provide a range of likely values, using the lowest measured value (0.4 pg/m^3), the median (201 pg/m^3), and highest measured (2644 pg/m^3) total PBDE levels.[45] The PBDE levels in automobile air were assumed to be the same for the general population and the electronic recycling facility workers. PBDE levels in outdoor air were estimated using data published from the CARB study that reported a median outdoor total PBDE concentration of 130 pg/m^3 at the University of California-Davis, which was used for both the exposed workers and the general population values.[36] The levels found by Cahill et al. were comparable to previously reported PBDE air levels in an urban US environment.[46]

Results and Discussion

Ratios of total PBDE exposure for the electronic recycling facility workers compared with the general population ranged from 6:1 to 33:1. Estimates depend heavily on assumptions about several components of intake for which little information exists. In the scenarios using the lower estimate total PBDE level in the dust at the electronic recycling facility, the ratio ranged from around 6:1 to 8:1, whereas the ratio ranged from around 13:1 to 33:1 using the upper estimate value. We conclude that the PBDE exposure to the workers at the California electronic recycling facility is dramatically elevated when compared with the US general population.

This article presents evidence, for occupational medicine physicians and related health workers, that high levels of PBDEs in air at a US electrical recycling facility can lead to excess worker exposure to these toxic and persistent chemicals. The estimated intake is believed to be several fold higher than would be expected for the general population not exposed to such high levels of PBDEs. The estimates are derived from reviewing data from a California facility and synthesis of data from other published reports on levels of PBDE intake from food, dust, and air, when available. There was a considerable amount of variation in the methods of sample collection, particularly in air and dust sampling, congeners measured, and analytical techniques used in the literature referenced in this study.[36,37,40–42,45] This led to an unavoidable level of uncertainty and variability for our estimates. In addition, our estimates rely on data from one electronics recycling facility which lacked emission control, dust suppression measures, or personal protective equipment for workers.[36,37] The literature describing PBDE levels in occupational settings or workers in the United States is currently limited.[28,36,37] Future similar studies could be improved by study of other facilities and their workers and utilization of highly qualified laboratories performing analyses of both blood and environmental samples using consistent methodology. Further research is also needed to determine average daily amounts of dust and dirt ingestion, as estimates in the literature vary by up to 200-fold.[39]

The research on occupational exposure to PBDEs is more limited than some other persistent organic pollutants. This is partly because PBDEs were introduced into commercial use as additive flame retardants in the 1970s and the potential for worker intake and toxicity was not immediately recognized. A review of the literature also reports increased PBDE body burden by electronic recycling workers in a number of countries, demonstrated in some cases by measurement of PBDEs in worker blood. In one study from Sweden, it was shown that improved worker safety measures did lead to lowering of blood PBDE levels.[33] In the air measurements taken at the California electronic recycling facility, BDE 209 was the predominant congener measured, comprising more than 90% of the total PBDEs measured in the samples taken when the electronics shedder was in operation.[36,37] This is consistent with the fact that the Deca-BDE commercial mixture is mainly (97% to 98%) BDE 209 and is used extensively in the high-impact polystyrene used in computer cases.[47]

When occupational health physicians and other health professionals suspect PBDE exposure, congener specific measurement of PBDEs in environmental and biological (blood) samples is indicated. If elevated levels are found this would suggest that both improved industrial hygiene and personal protective measures should be implemented. Periodic medical monitoring of highly exposed workers seems to be indicated. Although the exact toxicity in humans of the various PBDE congeners has not yet been determined, human as well as animal studies show a correlation between higher levels of PBDEs and certain adverse health consequences as discussed in the Introduction.[12–23] Evidence of ill health effects is stronger at this time in toxicological than human studies, but for a number of reasons it seems to us reasonable for medical, ethical, legal, and financial reasons to implement worker protection measures at this time as indicated despite some uncertainties.

Further study is clearly indicated to determine the range of levels of PBDEs in air and dust at other electronic recycling facilities as well as near plants. Additionally, workers' and nearby residents' blood levels of PBDEs should be determined for a number of facilities. Congener patterns in the environment and in blood may help suggest the source of the PBDEs. However, environmental and metabolic alterations may have occurred after the PBDEs were added to manufactured products which may make this not a trivial endeavor. Finally, it seems to us reasonable that health studies should be conducted periodically on highly exposed workers because of the persistent, toxic, and bioaccumulative nature of PBDEs.

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