Polybrominated Diphenyl Ethers (PBDEs) in U.S. Mothers' Milk

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No previous reports exist on polybrominated diphenyl ether (PBDE) congeners in human milk from individual U.S. mothers. This article on PBDEs is an extension of our previous studies on concentrations of dioxins, dibenzofurans, polychlorinated biphenyls, and other chlorinated organic compounds in human milk in a number of countries. PBDE commercial products are used as flame retardants in flexible polyurethane foam (penta-BDE), in acrylonitrile-butadiene-styrene resins (octa-BDE), and in high-impact polystyrene resins (deca-BDE). Their use is permitted in the United States but is banned in some European countries because of presumed toxicity, demonstrated persistence, and bioaccumulation. Different commercial products can be found in various consumer products such as television sets, computers, computer monitors and printers, carpets, and upholstery. Analyses of human levels of these compounds suggest low but rising levels in European human milk, which may have peaked, at least in Sweden, in the late 1990s. Very few data exist on levels of PBDEs in humans in the United States, and none from milk from individual nursing mothers. To address this issue, we analyzed 47 individual milk samples from nursing mothers, 20–41 years of age, from a milk bank in Austin, Texas, and a community women's health clinic in Dallas, Texas. Up to 13 PBDE congeners were measured. The concentrations of the sum of PBDE congeners varied from 6.2 to 419 ng/g (or parts per billion) lipid, with a median of 34 ng/g and a mean of 73.9 ng/g lipid. The PBDE levels in breast milk from Texas were similar to levels found in U.S. blood and adipose tissue lipid from California and Indiana and are 10–100 times greater than human tissue levels in Europe. Their detection in breast milk raises concern for potential toxicity to nursing infants, given the persistence and bioaccumulative nature of some of the PBDE congeners. These results indicate a need for more detailed investigation of the levels of PBDE in people and food, as well as determining if animal fat in food is the major route of exposure of the general U.S. population. Other routes of intake may also be significant. *Key words:* **brominated diphenyl ethers, brominated flame retardants, human milk, nursing mothers.** *Environ Health Perspect* **111:1723–1729 (2003). doi:10.1289/ehp.6466 available via** *http://dx.doi.org/* **[Online 5 August 2003]**

Synthetic halogenated compounds, including some of the persistent organic pollutants (POPs) such as chlorinated dioxins, dibenzofurans, and polychlorinated biphenyls (PCBs), have been identified as global environmental and human contaminants over the past 30 years. Some brominated flame retardants can also be persistent synthetic environmental contaminants. Within this group, brominated diphenyl ethers (BDEs) are one class of brominated flame retardants used in large amounts in the United States. Three commercial products are available: penta-BDE, octa-BDE, and deca-BDE. They are used as flame retardants in electrical appliances, including television sets, computers, computer printers, and fax machines, as well as in carpets and furniture upholstery [Bromine Science and Environmental Forum (BSEF) 2001]. These commercial mixtures differ in content of specific polybrominated diphenyl ether (PBDE) congeners, which in turn differ in their bioavailability, bioaccumulation, and toxicologic properties (de Wit 2002; Hardy 2002a, 2002b; McDonald 2002).

Regarding available commercial products, deca-BDE consists almost exclusively of deca-substituted BDE-209 (97%), with some 3% nona-BDE. In 2001, about 24,500 metric tons of penta-BDE was marketed in the United States. Smaller amounts of octa-BDE and penta-BDE mixtures are produced, 1,500 and 7,100 tons a year, respectively (BSEF 2001). Octa-BDE commercial mixtures include some hexa-BDE but mainly hepta-BDE and octa-BDE congeners, some nona-BDE and a very small amount of deca-BDE congeners. Almost all (98%) of the global penta-BDE is produced and used in the United States (BSEF 2001). The major use for penta-BDE has been in flame-retarding polyurethane foam, which is widely used in furniture upholstery. It consists of tetra-, penta-, and hexa-brominated congeners, especially BDE-47 (tetra), BDE-99 (penta), and BDE-153 (hexa), but also BDE-100 (penta) and BDE-154 (hexa) (Hale et al. 2002; de Wit 2002).

Lower brominated congeners, the tetra-BDEs and penta-BDEs, bioaccumulate to a greater degree than do the higher brominated BDEs such as deca-BDE. This may be caused by degradation of higher brominated congeners [International Program on Chemical Safety (IPCS) 1994]. Although the debromination of deca-BDE occurs under experimental conditions, it is not clear whether this decomposition occurs in the environment (Eriksson et al. 1998; Olsman et al. 2002). Results of a 2-year chronic rodent bioassay suggest that the deca-BDE mixture may be a possible human carcinogen, although this effect was observed in laboratory animals only at very high levels of exposure [National Toxicology Program (NTP) 1986]. Octa-BDE and penta-BDE are more bioactive, with possible endocrine, hepatic, reproductive, and neurodevelopmental toxicities (Branchi et al. 2002; Darnerud and Thuvander 1999; Darnerud et al. 2001; Eriksson et al. 1998, 1999, 2001; Fowles et al. 1994; Gillner and Jakobsson 1996; Hallgren and Darnerud 1998, 2002; Hallgren et al. 2001; Hardy 2002a, 2002b; Howie et al. 1990; McDonald 2002; Meerts et al. 1998, 2001, 2002; Morse et al. 1993; Pijnenburg et al. 1995).

Although levels of the dioxins, dibenzofurans, PCBs, and other organochlorines appear to be decreasing in humans living in industrialized countries over the past decades (Fürst 2001; Fürst and Päpke 2002; Fürst et al. 1994; Liem et al. 1995; Päpke 1998; Schecter et al. 2000; Smith 1999), levels of BDEs seem to be rising in some European countries (Noren and Meironyte 1998, 2000). Recently, the lower brominated PBDEs have been found in humans, in a small number of U.S. studies of blood and adipose tissue (Mazdai et al. 2003; Petreas et al. 2003; She et al. 2000, 2002; Sjödin et al. 2001) and Canadian milk studies (Ryan and Patry 2000, 2001; Ryan et al. 2002). Six congeners

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(BDE-47, BDE-99, BDE-100, BDE-153, BDE-154, and BDE-183) were measured in 12 fetal–maternal pairs in Indiana (Mazdai et al. 2003). Five congeners (BDE-47, BDE-99, BDE-100, BDE-153, and BDE-154) were measured in 23 adipose tissue samples collected from women living in the San Francisco Bay (California) area (She et al. 2000, 2002). She et al. (2002) measured the most prevalent congener, BDE-47, in 32 adipose and 50 serum samples. BDE-47 levels in these California women ranged from 5 to 510 ng/g (or parts per billion) lipid, with a median of 16.5 ng/g (Petreas et al. 2003). Levels of PBDEs (sum of seven congeners) in Canadian milk increased by about an order of magnitude between 1992 and 2002, from 3.0 ng/g (n = 72) to 22 ng/g (n = 92) (Ryan et al. 2002). Although human fat, blood, and milk levels detected in European countries are about 10 times lower than those found in Canada or the United States, in Sweden, for example, PBDE levels showed an exponential increase over the period from 1972 to 1997—from 0.07 ng/g to 4.02 ng/g in human milk (sum of nine BDE congeners), doubling about every 5 years (Meironyté Guvenius et al. 1999). A 9-fold increase in PBDE levels from 1977 to 1999 was observed in Norwegian stored blood samples (Thomsen et al. 2002). PBDE levels peaked in Sweden in 1997, after which a slight decrease was observed. This may have been the result of a "voluntary" ban on penta-BDE products in Sweden (Betts 2002) and some other European countries since the early 1990s. Levels in blood and milk in other European countries are similar to Swedish levels (Darnerud et al. 1998, 2002; Jakobsson et al. 2002; Schroeter-Kermani et al. 2000; Strandman et al. 2000; van Bavel et al. 2002). Comparison of the measured levels in most of these studies may be limited by the relatively small number of samples, different sampling procedures, and analysis conducted in laboratories using different methodologies. However, it is highly unlikely that the magnitude of the observed difference is only because of methodologic differences. The European Union (EU) will officially ban production, use, and import of penta-BDE and octa-BDE products in 2004 (European Parliament 2002). The decision about the ban of deca-BDE, which is still extensively used, is pending the outcome of the EU risk assessment.

BDE-47, BDE-99, BDE-100, and sometimes BDE-153 or BDE-154 dominate in environmental and human samples. BDE-47, BDE-99, BDE-153, and BDE-154 are major components of penta-BDE products. BDE-153 and BDE-154 are also found in octa-BDE. It is not clear how these relatively persistent toxic chemicals enter humans. With dioxins and dioxin-like chemicals, almost all enter the general population through the food chain, through meat, fish, or dairy products, as do many other fat-soluble chemicals. PBDEs may enter humans through food (Darnerud et al. 2001), by ingestion of dust (Knoth et al. 2002; Leonards et al. 2001), or by inhalation of some BDE congeners at home or on a job in the electronics and computer industries (Jakobsson et al. 2002; Johnson and Olson 2001; Sjödin et al. 1999, 2001, 2003). Dermal absorption in nonoccupational settings seems unlikely to substantially contribute to the elevated PBDE levels in the general population.

Although considerable data exist documenting the toxicity of dioxins, dibenzofurans, and PCBs [Agency for Toxic Substances and Disease Registry (ATSDR) 1994, 1998, 2000; International Agency for Research on Cancer (IARC) 1997; Institute of Medicine 1996, 1998, 2002; Schecter 1994; Schecter and Gasiewicz 2003; U.S. Environmental Protection Agency (EPA) 1984], fewer data exist on the toxicology of PBDEs. However, the information available does indicate the potential for neurodevelopmental and peripheral nervous system damage, endocrine disruption, and cancer (Darnerud et al. 2001; de Wit 2002; McDonald 2002). Ability of some PBDEs (BDE-47, BDE-99, BDE-153, and BDE-209) to disrupt thyroid hormone homeostasis and adversely affect behavioral development and cause learning deficits in rodents is of particular concern regarding potential exposure (Branchi et al. 2002; Eriksson et al. 2001, 2002; Lichtensteiger et al. 2003; Stoker et al. 2003; Viberg et al. 2002). Elevated levels of these compounds may thus represent a risk, especially to the developing fetus and nursing newborn. A recent study in Indiana showed that the individual fetal blood concentration did not substantially differ from the corresponding maternal concentration, ranging from 15 to 580 ng/g lipid in mothers and from 14 to 460 ng/g lipid in fetal serum (Mazdai et al. 2003). These U.S. levels were 106-fold and 69-fold higher for fetal and maternal serum, respectively, than levels found in maternal and fetal blood in a similar Swedish study (Meironyté Guvenius et al. 2003).

The detection of 200 ng/g lipid of PBDE congeners in a recent pooled milk sample (n = 20) from Austin, Texas, and Denver, Colorado (Päpke et al. 2001), led us to investigate in more detail the concentration and distribution of up to 13 PBDE congeners in milk from 47 individual human milk donors in Texas.

Materials and Methods

Sample collection. Human milk was obtained from volunteer U.S. donors between August and December 2002 from the Austin Mothers' Milk Bank in Austin and from University of Texas Southwestern Medical Center community women's health clinics in Dallas, Texas. We will further refer to samples from Austin as "milk bank" samples, and to those from Dallas as "clinic" samples. A total of 24 milk bank samples from Austin and 23 clinic samples from Dallas were available for this study. Milk samples were collected by manual expression in most of the cases; only a few women used a breast pump. Information on age, height, weight, and weeks of nursing was available from most of the participants, who provided these data and milk samples after signing the Institutional Review Board–approved informed consent documents required by the participating institutions. Average age was 30.5 years for the milk bank cohort and was 26.6 years for the clinic cohort (Table 1). Although information on ethnic background and recent as well as past residence was available for the clinic cohort in the study, this information was not available for the milk bank cohort. Of 24 participants in the clinic sample, 13 were born in Mexico. Usually, about 30 mL milk was collected in chemically cleaned glass containers. It was frozen shortly after collection and shipped on dry ice to the German and Canadian laboratories for PBDE analysis. The PBDE congener analyses were conducted by two experienced analytical laboratories, ERGO Research in Hamburg, Germany, and Health Canada in Ottawa, Ontario. Both are certified by the World Health Organization (WHO) for congener-specific analysis of dioxins, dibenzofurans, and PCBs in human milk, blood, and food (International Comparisons on Dioxins 2001; WHO 1991).

ERGO Research chemical analyses. The German laboratory analyzed 13 PBDE congeners (BDE-17, BDE-28, BDE-47, BDE-66, BDE-77, BDE-85, BDE-99, BDE-100, BDE-138, BDE-153, BDE-154, BDE-183, and BDE-209) in 23 clinic milk samples from Dallas. All analyses were performed following the isotope dilution method. Twelve native standards (^{12}C-labeled BDE-17, BDE-28, BDE-47, BDE-66, BDE-77, BDE-85, BDE-99, BDE-100, BDE-138, BDE-153, BDE-154, and BDE-183) were obtained from Cambridge Isotope Laboratories (Andover, MA, USA). BDE-209 was obtained from Wellington Laboratories (Guelph, Canada). Out of seven internal ^{13}C-labeled standards, six were puchased from Wellington (BDE-28, BDE-47, BDE-99, BDE-153, BDE-154, and BDE-183); BDE-209 was obtained from Cambridge Isotope Laboratories. Silica gel, alumina oxide, sodium sulfate, and potassium oxalate of the highest purity commercially available were used.

Before extraction, the mixture of seven internal BDE standards was added to the sample (500 pg for each congener except BDE-209, which was 50,000 pg/sample). We

extracted 5 mL human milk three times with pentane, after adding 5 mL water, 1 mL potassium oxalate solution, 10 mL ethanol, and 5 mL ether. The extract was washed with water and dried over sodium sulfate. After solvent evaporation, gravimetric lipid determination was performed. The extract was cleaned up by acid treatment and passed through activated silica gel and an alumina oxide column. The final extract was reduced in volume by a stream of nitrogen. The final volume was 50 µL containing ^{13}C-labeled BDE-139 for recovery standard. Methods have been described elsewhere (Päpke et al. 2001; Schroeter-Kermani et al. 2000).

The measurements were performed using high-resolution gas chromatography/high-resolution mass spectrometry at a resolution of 10,000 using a DB-5 column (30 m, 0.25 mm inner diameter, 0.1 µm film) for gas chromatographic separation. The two most abundant masses were used for measurement (M^+ for tri- and tetra-BDE, and $M^{-2}Br^+$ for penta- to deca-BDE). The identification of PBDEs was based on retention time and correct isotope ratio. The quantification was performed using internal and external standards.

Reduction of solvents and control of blank data are important steps in quality control when analyzing PBDEs in ultratrace levels. Solvents and reagents were tested before the laboratory procedures. All glassware was rinsed with analytical-grade solvents before use. Silica gel and sodium sulfate were prewashed. Rotary evaporators were not used in order to reduce the risk of contamination. No plastic

Table 1. Concentrations of PBDE congeners in breast milk from nursing mothers in Texas in 2001 (ng/g lipid).

Sample no.	Percent lipid	Mother's age (years)	Nursing (weeks)	PBDE congener 17	28	47	66	77	85	99	100	138	153	154	183	209	ΣPBDE
1[a]	4.8	31	3	ND	0.2	2.9	0.02	ND	0.08	0.7	0.7	ND	1.5	0.06	ND	ND	6.2
2[a]	1.3	29	3	ND	0.3	3.5	ND	ND	0.08	0.7	0.5	ND	0.9	0.06	0.06	ND	6.2
3[a]	2.1	23	74	ND	0.2	3.9	0.06	ND	0.11	1.5	0.6	ND	0.4	0.08	ND	ND	6.9
4[b]	4.8	32	21	—	0.3	3.5	0.14	—	0.08	1.6	0.7	0.09	1.4	0.09	0.04	—	8.0
5[a]	2.6	22	40	0.01	0.3	6.3	0.05	ND	0.23	2.8	1.2	ND	0.7	0.20	0.05	ND	11.8
6[a]	3.6	36	109	ND	0.4	7.8	0.09	ND	0.23	2.4	1.1	0.01	0.4	0.11	ND	ND	12.5
7[a]	1.9	32	20	ND	0.7	8.2	0.04	ND	0.22	1.3	1.7	ND	0.9	0.12	0.08	ND	13.3
8[a]	6.3	25	2	ND	0.4	7.9	0.02	ND	0.38	2.3	2.7	ND	0.8	0.15	0.06	ND	14.7
9[b]	2.1	35	29	—	0.7	8.8	0.19	—	0.17	1.5	1.7	0.16	2.0	0.06	0.03	—	15.2
10[a]	5.5	32	30	ND	0.4	8.0	0.01	ND	0.44	2.9	2.0	ND	0.9	0.14	0.24	0.48	15.6
11[a]	5.0	20	2	0.01	1.1	10.9	0.05	ND	0.18	2.0	2.4	ND	1.3	0.17	0.04	ND	18.1
12[a]	3.4	23	3	0.01	0.4	8.0	0.03	ND	0.35	3.1	2.7	ND	2.0	0.21	0.61	0.93	18.3
13[b]	1.3	32	16	—	0.8	10.5	ND	—	0.35	2.5	2.2	0.19	2.0	0.12	0.03	—	18.6
14[a]	3.4	25	NA	0.02	1.1	12.0	0.13	ND	0.23	2.5	1.8	ND	1.3	0.15	0.08	1.85	21.1
15[a]	2.9	21	29	0.03	0.5	10.7	0.09	ND	0.27	5.5	2.1	ND	0.9	0.35	0.07	2.74	22.4
16[b]	3.5	30	30	—	0.7	6.9	ND	—	0.12	1.3	4.6	0.41	8.5	0.19	0.06	—	22.8
17[a]	1.0	23	2	ND	0.9	14.2	0.11	ND	0.37	3.7	2.6	ND	1.3	0.24	0.09	ND	23.5
18[b]	3.7	23	19	—	0.7	13.2	0.57	—	0.29	3.7	2.5	0.29	1.9	0.17	0.06	—	23.5
19[a]	3.2	26	2	ND	1.3	17.4	0.19	ND	0.35	4.0	2.1	ND	0.7	0.18	ND	ND	26.2
20[b]	3.5	34	22	—	1.0	14.3	0.29	—	0.46	5.7	3.6	0.25	1.4	0.20	0.10	—	27.3
21[b]	3.1	33	60	—	1.4	18.4	ND	—	0.25	4.1	1.8	0.09	2.1	0.16	0.06	—	28.3
22[b]	4.9	38	26	—	1.2	17.4	ND	—	0.34	7.1	2.3	0.14	0.6	0.30	0.12	—	29.6
23[a]	3.4	30	2	0.01	0.7	15.2	0.06	ND	0.42	4.2	2.3	ND	3.0	0.22	0.03	3.97	30.1
24[a]	5.1	28	53	0.01	1.1	20.0	0.18	ND	0.53	5.1	3.9	0.01	2.7	0.32	0.11	ND	34.0
25[b]	4.7	35	NA	—	1.3	20.9	0.56	—	0.31	6.3	2.9	0.14	1.2	0.22	0.17	—	34.1
26[a]	1.1	41	38	0.02	1.5	19.5	0.11	ND	0.41	3.4	3.3	ND	7.7	0.18	ND	ND	36.1
27[b]	6.1	37	25	—	7.6	17.2	1.19	—	0.35	6.1	2.3	0.18	1.7	0.27	0.05	—	36.8
28[b]	3.0	27	51	—	1.4	28.2	ND	—	0.51	7.5	2.9	0.25	0.7	0.20	0.75	—	42.4
29[b]	4.8	25	NA	—	1.8	21.6	0.94	—	0.50	9.4	4.4	0.47	5.8	0.60	0.06	—	45.5
30[b]	2.2	39	11	—	1.1	26.8	ND	—	0.75	8.9	5.3	0.58	2.0	0.45	0.10	—	46.0
31[b]	5.6	34	NA	—	2.7	31.8	ND	—	0.42	7.8	3.1	0.09	0.8	0.22	0.10	—	47.0
32[b]	3.4	27	10	—	2.6	30.1	0.75	—	0.57	5.9	6.5	0.32	2.5	0.34	0.09	—	49.6
33[a]	2.8	20	13	0.02	1.1	31.3	0.17	ND	0.13	10.2	5.9	0.02	1.5	0.48	0.11	2.96	53.9
34[b]	4.0	20	13	—	3.4	33.5	2.32	—	0.49	5.8	5.8	0.27	2.6	0.32	0.06	—	54.6
35[b]	3.3	26	17	—	1.4	32.3	0.70	—	0.66	9.6	5.7	0.46	12.4	0.51	0.05	—	63.8
36[b]	2.2	20	16	—	1.4	25.5	0.75	—	0.76	8.0	18.3	1.75	18.3	0.94	0.08	—	75.8
37[a]	1.1	22	51	0.04	2.2	44.3	0.55	0.03	0.64	10.8	8.1	0.02	14.7	0.56	ND	ND	81.9
38[b]	4.3	29	38	—	5.2	34.8	0.61	—	1.94	9.8	29.2	1.20	14.5	0.96	0.10	—	98.2
39[a]	1.0	26	22	0.02	1.7	54.7	0.54	ND	1.63	23.6	10.0	ND	4.8	1.15	0.07	ND	98.2
40[b]	4.9	32	38	—	3.4	49.7	1.21	—	1.20	7.7	21.1	1.40	16.3	0.93	0.15	—	103.1
41[b]	3.4	30	9	—	3.9	63.1	3.13	—	2.81	30.1	16.2	3.29	17.2	1.94	0.08	—	141.6
42[a]	1.2	21	2	0.10	10.1	120.9	1.68	0.06	2.64	30.3	20.1	0.13	16.4	2.07	ND	ND	204.3
43[b]	1.2	33	15	—	8.0	139.6	ND	—	4.12	44.6	23.0	4.47	21.8	2.76	0.18	—	248.5
44[a]	1.0	23	2	0.06	3.6	172.4	1.14	ND	6.28	69.8	31.9	0.08	8.4	3.07	0.16	ND	296.9
45[b]	2.1	34	13	—	7.5	199.6	6.67	—	7.73	108.5	31.7	4.12	6.9	3.62	0.36	—	376.7
46[a]	1.7	33	47	0.18	6.1	196.2	2.07	0.16	6.46	111.0	31.0	0.27	15.5	7.21	1.32	8.24	385.5
47[b]	5.1	29	28	—	16.1	271.5	3.16	—	6.29	50.4	47.4	6.86	14.1	2.87	0.12	—	418.8
Mean		28.64	24.56	0.02	2.4	40.8	0.65	0.01	1.15	14.0	8.2	0.60	5.3	0.76	0.13	0.92	73.9
Median		29	20	0.01	1.2	18.4	0.14	NA	0.41	5.7	2.9	0.09	2.0	0.22	0.07	NA	34.0
SD		5.70	22.26	0.04	3.1	59.4	1.19	0.04	1.89	24.6	10.8	1.37	6.1	1.30	0.23	1.96	103.3
Minimum		20	2	ND	0.2	2.9	ND	ND	0.08	0.7	0.5	ND	0.4	0.06	ND	ND	6.2
Maximum		41	109	0.18	16.1	271.5	6.67	0.16	7.73	111.0	47.4	6.86	21.8	7.21	1.32	8.24	418.8

Abbreviations: NA, not available; ND, not detected. ΣPBDE includes 10 BDE congeners for the Austin samples (BDE-28, BDE-47, BDE-66, BDE-85, BDE-99, BDE-100, BDE-138, BDE-153, BDE-154, and BDE-183) and three additional congeners for the Dallas samples (BDE-17, BDE-66, and BDE-209).
[a]Dallas samples. [b]Austin samples.

equipment was used. For quality control, a laboratory blank and a quality control pool of human milk was run with each batch of 10 samples. Quantification was only done if the sample level was at least twice the blank level.

Health Canada chemical analyses. The Canadian laboratory analyzed 10 PBDE congeners (BDE-28, BDE-47, BDE-66, BDE-85, BDE-99, BDE-100, BDE-138, BDE-153, BDE-154, and BDE-183) in 24 milk bank samples from Austin. Three PBDE congeners, BDE-17, BDE-77, and BDE-209, were not measured in this laboratory because levels below the limit of detection were expected for these congeners for the majority of milk samples. Six ^{13}C-labeled BDEs were purchased as two mixtures from Wellington Laboratories. Most of the 18 ^{12}C-labeled BDE congeners were obtained from Cambridge Isotope Laboratories.

A mixture of 500 pg each of six ^{13}C-labeled PBDE congeners was added to 30 g human milk (~0.4–1.0 g milk fat). The samples were homogenized and extracted with acetone–hexane (a small aliquot was used for the lipid determination gravimetrically), defatted with concentrated sulfuric acid, adsorbed on acid silica, and separated on activated magnesium silicate. Chromatography on Florisil was adjusted so that the less polar PCBs were separated from the bulk of the PBDEs (Ryan and Patry 2001; Ryan et al. 2002).

A 30 M methyl silicone gas chromatographic column effected separation of the mono- to hepta-BDE homologs. Detection was performed with mass spectrometry in the electron impact mode at 10,000 resolution with monitoring of six groups of 5–10 ions per group of either M^+ or $M^{-2}Br^+$ (two ions per analyte). Quantification was carried out with isotope dilution using a five-point linear calibration curve containing 18 BDE congeners, six ^{13}C-labeled BDE surrogates, and three recovery or performance standards (PCB-200, PCB-209, and decabromobiphenyl). The latter are used to check performance of the gas chromatograph and to calculate recovery of surrogates.

Each batch of 8–10 unknown samples contained a laboratory reagent blank and a quality control human milk repeat sample. The former was used to measure the contribution of BDEs in the laboratory to the total signal, which was then subtracted from the signal in the unknown samples before quantification. The repeat human milk quality control sample was used as an ongoing measure of laboratory precision and reliability.

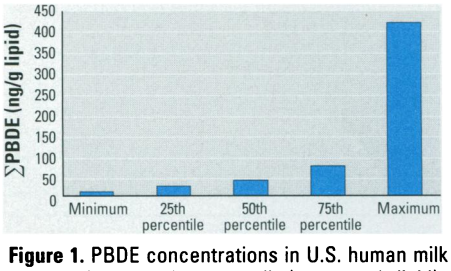

Figure 1. PBDE concentrations in U.S. human milk samples from 2002 by percentile (n = 47; ng/g lipid).

Results

Table 1 lists 13 major PBDE congeners, the sum of all the PBDE congeners (ΣPBDE), percentage of lipid in each of the 47 individual milk samples, age of each mother, and length of nursing. Table 1 further shows that the range for the ΣPBDE varied from 6.2 to 419 ng/g lipid, with a mean of 73.9 ng/g and a median 34.0 ng/g. The table is arranged by increasing levels of PBDE congeners. We should note the presence of BDE-209 in 6 of 23 clinic samples, indicating that despite a lower bioavailability compared with the other lower brominated congeners, some of it is absorbed and is present in human milk samples. BDE-17, BDE-77, and BDE-209 measured in the clinic samples in addition to 10 congeners measured in both milk bank and clinic samples contributed < 1% to the ΣPBDE; therefore, we present only one ΣPBDE including all 13 congeners, where available.

The milk bank participants were on average about 4 years older than clinic participants (mean age, 30.5 vs. 26.6 years). ΣPBDE levels were not correlated with age in the whole sample (r = –0.04) or in the milk bank or clinic samples. The median and mean ΣPBDE levels in the milk bank samples were 45.8 ng/g and 85.7 ng/g, respectively. In the clinic samples, the median was 20.4 ng/g and the mean was 61.6 ng/g. BDE-47 contributed most to the ΣPBDE (54%), followed by BDE-99 (16.8%), BDE-100 (8.5%), and BDE-153 (5.9%).

We do not know the ethnicity of participants in the milk bank samples, but information obtained from the staff at the milk bank suggests that the majority of women were white. In the clinic samples, 13 women were born in Mexico and have been living in the United States on average 5.3 years, with a range from 6 months to 12 years. We did not observe any substantial difference between PBDE levels in women born outside the United States and the rest of the clinic samples. Hispanic women had similar PBDE levels, with a median ΣPBDE of 20.4 ng/g compared with 22.7 ng/g in non-Hispanic women.

The length of time nursing in weeks also did not seem to correlate with the ΣPBDE concentrations (r = –0.07) in the whole sample or in the milk bank or clinic samples. The length of the most recent nursing was shorter in the clinic group (26.6 vs. 30.6 weeks), but six of the clinic sample participants had been nursing only for about 2 weeks when milk was collected. The correlation did not change substantially when the total length of lactation for all children was used in calculations. The number of children of subjects did not correlate with the PBDE concentrations (data not shown).

In Figure 1, the ΣPBDE concentrations are shown in quartiles, from minimum to maximum. Figure 2 shows the ΣPBDE concentrations for each of the 47 women. Fifteen of the samples (32%) contain ΣPBDE > 50 ng/g, and the highest 10 samples contain ≥ 100 ng/g; the highest level of ΣPBDE in milk in these samples is 419 ng/g. Figure 3 shows a comparison of levels of BDE-47, BDE-99, and BDE-153 in human milk between several countries. Values for Germany (Schroeter-Kermani et al 2000), Canada (Ryan et al 2002; Ryan and Patry 2001), Sweden (Noren and Merionyte 2000), and Finland (Strandman et al. 2000) are compared with the U.S. data, showing higher levels for each in the U.S. milk.

Discussion

This is the first study of PBDEs in individual U.S. mothers' milk. Up to 13 PBDE congeners were analyzed in human milk from 47 individual women in the general population from two sources in Texas, a milk bank in Austin and community women's health clinics in Dallas. The findings show extremely elevated levels (10–100 times) in many participants compared with contemporaneous levels reported in

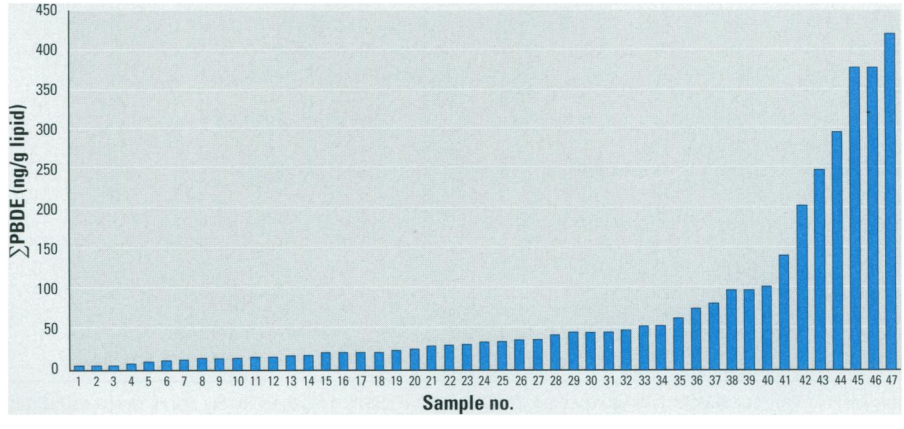

Figure 2. PBDE concentrations in individual U.S. human milk samples from 2002 (ng/g lipid).

Europe (Darnerud et al. 2001; Meironyté Guvenius et al. 1999; Schroeter-Kermani et al. 2000; Strandman et al. 2000; Thomsen et al. 2002). They also show very elevated levels in many of the women with no known occupational exposure. The women were white, African American, and Hispanic in origin. We found no apparent difference in concentrations between age groups or ethnic groups, but even though this is the largest individual U.S. human milk study for PBDEs, it is still a relatively small sample. The milk bank and clinic samples were analyzed by two experienced laboratories that had participated in numerous interlaboratory dioxin and dibenzofuran quality control studies (International Comparisons on Dioxins 2001; WHO 1991), but some of the differences observed could be due to different methodologies used. A human milk interlaboratory study conducted by the Canadian and German laboratories after our study was completed reported almost identical congener levels when using a pooled milk sample (Päpke O, Ryan JJ. Personal communication).

Two recent U.S. studies in California (Petreas et al. 2003) and Indiana (Mazdai et al. 2003) have measured PBDE levels in blood samples and adipose tissue and in fetal and maternal serum samples. Levels found in these two studies were also reported on a lipid basis and are similar in range to those found in the present study. These results suggest that there appears to be a similar range in different parts of the United States and that U.S. PBDE levels are at least 10 times and up to 100 times higher than those found in Europe. Data on potential sources of exposure indicate that PBDEs are present in food (Asplund et al. 1999; Huwe et al. 2000; Jacobs et al. 2001; Johnson and Olson 2001; Lind et al. 2002; Ohta et al. 2002; Zegers et al. 2001), land sludge (Pardini et al. 2001), and dust (Knoth et al. 2002; Leonards et al. 2001). It remains to be shown whether or not food represents a major source of PBDEs as it does with dioxins (Schecter 1994; Schecter and Gasiewicz 2003; Startin 1994; U.S. EPA 1984). In a recently published paper, Sjödin et al. (2003) reviewed human exposure to brominated flame retardants, especially PBDEs.

At present, only one study (n = 15) examined the partitioning ratio of PBDE congeners between adipose tissue, milk, and blood (Meironyté Guvenius et al. 2003). The results suggest that partitioning is close to 1:1. The partitioning previously reported for dioxin and dibenzofuran congeners varied in blood and adipose tissue from approximately 1:1 for 2,3,7,8-tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD), to 2:1 for octachlorinated dibenzodioxin (Schecter et al. 1991, 1998). The partitioning of persistent lipophilic compounds, including dioxins, between human milk and blood lipid was recently reviewed by Aylward et al. (2003). Schecter et al. (1989) have also shown that the partitioning of dioxins and related compounds in various organs of the human body is not always 1:1. Further studies should be conducted to more precisely estimate the partitioning for PBDE congeners and to increase confidence in using different matrices to estimate body burden.

The purpose of this study was to determine whether U.S. women have higher, equal, or lower milk PBDE levels than women in other countries. The answer is striking: the 47 individual U.S. women studied here had markedly higher levels in their breast milk compared to Europeans. This survey clearly indicates that high levels of PBDEs are found in U.S. women and can be transferred to the nursing infants, as shown recently by Mazdai et al. (2003) and Meironyté Guvenius et al. (2003). The effects of age, previous nursing, and food on levels of PBDEs in humans needs to be determined. This study, like the California study (Petreas et al. 2003) and the Swedish (Darnerud et al. 1998) and Norwegian (Thomsen et al. 2002) studies, did not show a positive association with age as has been found with dioxins, PCBs, and other POPs. Even though this association was not tested on a sufficiently large sample to draw a definitive conclusion, data from this and other studies appear to support a lack of increase in PBDE levels with age. Similar to age, and again unlike dioxins and PCBs, length of lactation did not seem to be associated with the PBDE levels. Whether this is because of the relatively short history of intensive PBDE use remains to be determined.

It should be noted that the current use of brominated flame retardants is the result of a need for safer consumer products, that is, products that are less likely to burn in fires. It is estimated that many deaths are avoided in the United States each year by the use of brominated flame retardants, and children are at special risk of death and injury in fires.

Further studies need to be conducted on PBDE levels in milk and blood, in women from different locations, of ethnic groups and different ages, and with different nursing histories, as well as in males and children. Health consequences to the nursing infant as well as the adult from PBDEs at the levels found need further study. There are particular concerns especially about infant health because the fetus and the developing child are more sensitive than adults to the effects of exogenous chemical compounds, including PBDEs in breast milk or diet. Measurement of PBDE levels in meat, fish, dairy products, air, and dust should help determine routes of exposure, adding to the limited data available today (Asplund et al. 1999; Huwe et al. 2000; Jacobs et al. 2001; Johnson and Olson 2001; Knoth et al. 2002; Leonards et al. 2001; Lind et al. 2002; Ohta et al. 2002; Zegers et al. 2001). Occupational health studies of potentially exposed workers may also be helpful in identifying the source of these persistent and toxic halogenated organics. Clearly, much further research is needed to determine the levels and distribution of PBDEs in the U.S. population, routes of intake, and their health effects.

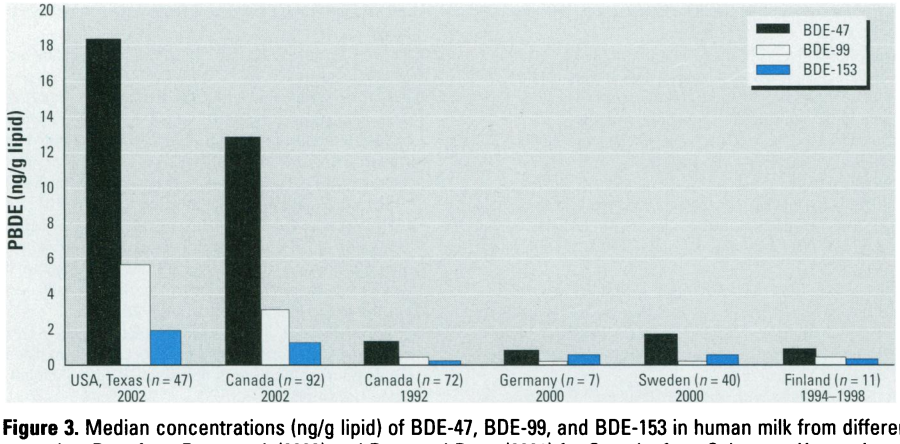

Figure 3. Median concentrations (ng/g lipid) of BDE-47, BDE-99, and BDE-153 in human milk from different countries. Data from Ryan et al. (2002) and Ryan and Patry (2001) for Canada, from Schroeter-Kermani et al. (2000) for Germany, from Noren and Merionyte (2000) for Sweden, and from Strandman et al. (2000) for Finland.

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