The research of human exposure to polybrominated diphenyl ethers and perfluorooctane sulfonate

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As two kinds of emerging chemicals, the pollution of polybrominated diphenyl ethers (PBDEs) and perfluorooctane sulfonate (PFOS) has been becoming a global environmental problem. Also, research of the transport, transfer, bioaccumulation in organism, and toxicology of these two kinds of pollutant is a hotspot in environmental sciences now. In this paper, we summarize and critically review the status and progress of PBDEs and PFOS exposure to human beings. Further, data analyses based on statistical methods are done to study the characters of PBDEs and PCBs concentrations in different regions in the world.

polybrominated diphenyl ethers, perfluorooctane sulfonate, human beings, breast milk, human blood, human tissue

Polybrominated diphenyl ethers (PBDEs) are widely used as brominated flame retardants (BFRs) in polyurethane foam, carpet, and electronic equipment such as computers and TV. In recent year, the global demand for PBDEs increases rapidly. In China, the production quantity of decabrominated diphenyl ether (deca-BDE) has ranked first among the largest BFRs since 1980s.

As a kind of additive BFRs, due to the lack of chemical bond binding, PBDEs can release to the ambient environment via the production, the use of these compounds, and the dismantling of the products to which these compounds are added, especially during electronic wastes (e-waste) recycling. PBDEs were initially determined in barracuda, eel, and sea trout in Sweden in 1981^[1]. And then this group of pollutant was continuously found in sea fish, mussel, and sediments, etc, in the worldwide sites^[2]. Jansson firstly suggested PBDEs should be attributed to a kind of global environmental pollutant in 1987^[3]. The focus on PBDEs pollution initialized a detailed investigation about persistent organic pollutants (POPs) in Sweden's human breast milk. In this paper, other POPs in breast milk such as polychlorinated biphenyl (PCBs) decreased from 1970s to 1990s, but for PBDEs, the concentrations were increas-

ing rapidly^[4]. From then on, more and more studies reported PBDEs in air, soil, water, biosample, and human bodies. Recent works indicated that the concentrations of PBDEs in different environmental matrixes and human being are increasing rapidly^[5-9]. Now, many countries including Europe, North America, Japan, and China have done related work to solve the environmental pollution of PBDEs.

Perfluorooctane sulfonate (PFOS) is a representative of polyfluoroalkyl compounds (PFCs), which are used in industrial and commercial products. Due to their special chemical properties, more than one hundred products of PFCs have been synthesized, which are used as lubricants, adhesives, paper coatings, and fire-fighting foams, etc.^[10-13]. The release of this kind substance to the ambient environment can occur via all kinds of pathway because of their usage. Recently, the publications about environmental behavior, toxicology, and current pollution of PFCs showed a rapid increasing trend and the risk assessment has been becoming a hotspot about

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PFCs.

In this paper, we focus on and review the status and progress of PBDEs and PFOS exposure to human beings. Attention is paid to the discussion about several main congeners of PBDEs including BDE47, 99, 100, 153, and 154. Among the numerous PFCs derivatives, PFOS and perfluorooctanoic acid (PFOA) were the most notable ones.

1 The toxicity of PBDEs and PFOS and intake pathway of human body

1.1 The toxicity of PBDEs and intake pathway of human body

Previous studies have proved that the toxicity of PBDEs varies much due to the degrees of bromination. Evidence shows that penta-BDE in commercial products may be developmental neurotoxicants, neurochemical and hormonal deficits for the model animals such as rats and rabbit, while octa-BDE can cause malformation for fetus. The work on the toxicity of deca-BDE suggested that deca-BDE does not have acute toxicity. But there is evidence proving that it can debrominate to lower brominated congeners under the environmental condition and in living body, and then increase the harm to ambient environment and human beings. Chen et al. revealed that both pure PBDE congeners and commercial PBDE mixtures had Ah receptor binding affinities like dioxin^[14]. Also, during the manufacturing PBDEs and combustion of production containing PBDEs, polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs), which have the chemical structures of polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) can be produced and released into environment^[15].

There are several pathways for PBDE to be intaken into human body: (1) PBDEs can be biomagnified through food chains and then enter human body via dietary. Fishes especially those having higher lipid are the main sources of PBDEs^[16]. (2) Breast milk is the main source of PBDEs for infant. Many reports have proved that high concentrations of BDE47, 99, and 153 can threaten children's health via maternal feeding^[17,18]. (3) PBDEs in furniture, electrical equipment, and other materials can release indoor air^[19], and human body is passively exposed to PBDEs by imbibing the dust and particle in air.

1.2 The toxicity of PFOS and intake pathway of human body

Previous work revealed that experimental rats showed

obvious decrease of body weight, poisoning of liver, muscle tremor, and even died with a high dose and by short period's exposure to PFOS^[20,21]. The study of organ toxicity showed that PFOA and PFOS can disturb fatty acid combining with liver fatty acid-binding protein, influence the metabolizability of fatty acid, and decrease the activity of all kinds of enzymes in liver cell^[22]. There is also other evidence proving that PFOS and PFOA can induce neurotoxicity^[23], hurt cardiac muscle^[24], influence the growth of embryo, and have procreation and inherited toxicity^[25,26].

The main intake paths of PFOS and PFOA for human body, which are similar to those of PBDEs, are via food intake, breath, and the biodegradation of other PFCs^[10].

2 The concentrations of PBDEs and PFOS in human bloods

2.1 The concentrations of PBDEs in human bloods

It is proved by experimental rats that BDE47 can enter living body through skin, which is perhaps also a pathway for PBDE to enter human bodies^[27,28]. Many researches have been focused on PBDEs in human tissues, blood, and breast milk. Figure 1 shows the concentrations of main congeners BDE47, 99, 100, 153, and 154 in human blood in the world^[29-44]. The database includes the concentrations of PBDEs in 1157 blood samples from 10 countries between 1977 and 2007. From the box chart we can find that the highest concentration of congener is BDE47, accounting for 47.9% of the total PBDEs. The next congener is BDE153, accounting for 17.3% of the total of PBDEs.

The concentrations of PBDE vary greatly from country to country (in a range of 0.44 ng/g and 71 ng/g (lipid)) and the highest occurs in the United States. Other studies also pointed out that the inhabitants in USA live in a relatively high exposure environment of PBDEs^[45]. In China, the PBDEs concentrations in human bloods are lower than those in Europe and North America.

Generally, PBDEs concentrations in human body have increased by 100-fold in the past 30 years. The investigation of human blood in Norway showed that the concentrations of PBDEs increased from 0.44 ng/g in 1977 to 3.1 ng/g in 1999. Correspondingly, the concentrations in Germany increased from 2.66 ng/g in 1986 to 4.53 ng/g in 1999. And the study in USA also showed a rapid increasing trend. PBDEs concentrations in American human body have increased by more than 10-fold in

Figure 1 The distribution of PBDEs concentrations in human blood from different countries. The insert figure is the box chart of concentrations of PBDEs.

recent years and those in Japanese human body are about 5-fold.

Principal component analysis (PCA) can project multidimensional data onto two-dimensional schematic, which is a better way to make comparison of the congener distributions. In order to further compare and analyze the characters of the concentrations in different regions, PCA was executed with SPSS 13.0 for Windows Release 13.0 (SPSS Inc., 1989–2006) and the full data sets of five main concentrations (BDE47, 99, 100, 153, and 154) were used in PCA. The first two principal components explained 94% of the variability of the data set. Principal component 1 versus principal component 2 is shown in Figure 2(a), which suggests that the PBDEs concentrations in USA's human blood were significantly higher than those in other countries. Sjödin also revealed that from 1985 to 1992, BDE47, 99, 100, 153 and the sum of PBDEs showed a linear increasing trend^[41]. Because the concentrations of human blood samples in USA are so high, the information in other countries can be concealed when executed PCA. So the database, which excluded the information of USA, was re-analyzed using PCA analysis. The result (Figure 2(b)) showed that in Asia, the concentrations of PBDEs in

human blood collected from South Korea were higher than those in China and Japan. In this work^[43], the researchers specially focused on PBDEs occupational exposure in incinerator workers and selected a group of the general population residing far from the sampling sites as the control samples. The investigation indicated that no obvious evidences proved that the concentrations in incinerator workers' bloods were higher than those in controlled human bodies. They considered that solid waste incinerators did not obviously influence the PBDEs concentrations in human body. But the incineration can produce other toxic compounds including PBDD/Fs and also increase the toxicity of the incinerator environments and the health risks or incinerator workers. Figure 2(b) also shows that in the United Kingdom, BDE-154 in blood is higher than that in other countries.

2.2 The concentrations of PFOS and PFOA in human blood

PFOS and PFOA are two main PFCs in environment and human body. The first study about PFCs in human blood was done in 1960s^[46]. Recently, based on the studies of PFOS and PFOA on the workers employed by PFCs production factories, the research work relating to

Figure 2 PCA results of the concentrations in human bloods from different countries. (a) For principal component 1, the loading values of BDE47, 99, 100, 153, and 154 are 0.918, 0.909, 0.880, 0.545, and 0.328, respectively; for principal component 2, the corresponding values are 0.378, 0.392, 0.459, 0.731, 0.908, respectively; (b) the PCA results except the data of USA. For principal component 1, the loading values of BDE47, 99, 100, 153, 154, and the sum of PBDEs are 0.943, 0.945, 0.900, 0.802, 0.072; for principal component 2, the corresponding values are -0.063, -0.001, 0.381, 0.213, 0.987.

PFOS and PFOA in human blood was carried out worldwide. The finished work included the studies about the concentration in human blood in USA, Colombia, Brazil, Italy, Poland, Belgium, India, Malaysia, South Korea, Japan, and China^[47–49]. Table 1 lists the concentrations of PFOS and PFOA in human bloods from different countries between 1974 and 2005. And the levels ranged from under limit of detection (LOD) to up to more than one thousand ng/mL.

Figure 3 exhibits PFOS and PFOA in whole blood and serum worldwide and the temporal trends in USA and Japan. The concentration of PFOS in most samples is higher than that of PFOA. Generally, the concentrations in Europe and North America are the highest in the world. In USA, the levels did not obviously change in 1974–2000, but in the period of 2000–2005, the concentration showed a rapid increase. In Japan, no obvious change of PFOS and PFOA concentrations was found between 2001 and 2004 although the pollution levels varied greatly from county to county.

The highest value occurred in USA^[52]. Ehresman et al. collected blood samples from participants employed by 3M Company including fluorochemical production workers, laboratory researchers, and administrative employees and found that the average concentrations of PFOS and PFOA in serum were 134 and 1046 ng/mL, respectively, and the highest was up to 880 and 7320 ng/mL, respectively. The average concentration in the whole blood was 68 and 535 ng/mL, respectively. They also found that the concentrations in laboratory re-

searchers were higher than those in production workers and administrative employees. The concentrations ratio of serum to plasma was about 1:1, which was independent of the level of concentrations measured.

The study about the concentrations in serum of South Korea showed that the concentration of PFOA was higher than that of PFOS, indicating that specific source existed in some districts in this country^[48].

3 The concentrations of PBDEs and PFOS in human breast milk

PBDEs can enter infant body via breast milk. Current researches found that the concentration level of PBDEs in human breast milk reached the concentration levels in other tissues^[67]. The concern about BFRs pollution in environment was just aroused from a detailed report about the PBDEs in Sweden's breast milk^[9,68]. In this report, other POPs showed a decreasing trend from 1970s to 1990s, but for PBDEs, the concentrations appeared a continuous increase. The concerned review pointed out that the concentrations of PBDEs in human breast milk have a 10-fold higher than those in 1970s and BDE47 is the main congener^[69].

Figure 4 is the box chart of the concentrations of PBDEs (BDE47, 99, 100, 153, and 154) in milk from 22 countries^[28,70–95]. Similar to the distribution of PBDEs in blood, the concentrations in milk varied greatly from country to country and from period to period. The concentrations of the total of PBDEs ranged from 0.07 to 384.6 ng/g (lipid). BDE47 and 153 account for 51.1%

Figure 3 The concentrations of PFOA and PFOS in blood in different countries. (a) PFOA and PFOS in whole blood; (b) PFOA and PFOS in serum with a temporal trend.

Table 1 The concentrations of PFOA and PFOS in different countries (ng/mL)

Country	Sampling time	No.	PFOS	No.	PFOA	Matrix	Ref
Japan	2003	10	10.3			whole blood	[50]
Japan	2003	15	8.9	15	nd	whole blood	[51]
Japan	2003	15	2.9	15	nd	whole blood	[51]
America	2004–2005	17	68	12	535	whole blood	[52]
America	2004–2005	299	4.9	299	1.6	whole blood	[53]
America	2001–2002	57	24.2	57	4.26	whole blood	[54]
Poland	2003		21		3.3	whole blood	[55]
Poland	2003	25	42.14	25	20.5	whole blood	[48]
Spain	2006	48	7.64	48	1.8	whole blood	[56]
Sweden	1997–2000	66	66	66	2.4	whole blood	[57]
China	2004	85	52.7	85	1.59	whole blood	[58]
Colombia	2003	56	8.28	56	6.16	whole blood	[48]
Brazil	2003	27	11.74	27	<20	whole blood	[48]
Belgium	1998–2000	20	16.3	20	4.82	plasma	[48]
Malaysia	2004	23	12.74	23	10	whole blood	[48]
Korea	2003	50	21.2	50	61.8	whole blood	[48]
America	1974	178	29.5	127	2.3	serum	[59]
America	1989	178	34.7	177	5.6	serum	[59]
America	1990–2002	23	31.1	23	11.6	serum	[60]
America	2000–2001	645	34.9	645	4.6	serum	[61]
America	2003	20	55.8	22	4.89	serum	[62]
America	1999–2000	238	31	238	4.2	serum	[63]
America	1999–2000	1562	30.4	1562	5.2	serum	[64]
America	2004–2005	18	134	12	1046	serum	[65]
Italy	2001	50	4.32	50	<3	serum	[48]
India	2000	45	1.85	45	3.38	serum	[48]
Japan	2002	38	16.15	38	8.68	serum	[48]
Japan	2003	3	27	–	–	serum	[48]
Sweden		17	33.4	–	–	plasma	[65]
Australia		40	23.4	–	–	serum	[65]
UK		13	14.2	–	–	plasma	[65]
Japan		22	21.47	22	10.7	serum	[66]

No., The number of samples.

and 18.1% of the total of PBDEs, respectively.

Figure 4 indicates that higher concentrations of PBDEs in milk occurred in North America. Thereinto, the study about PBDEs in breast milk from the northeast Pacific revealed that for some samples, BDE153 concentrations were higher than those of BDE47^[84]. In Asia, the concentrations showed obviously low levels compared with other regions. The concentration levels in milk from South Korea are similar to those from China and Japan, which is different from the results of blood. Further, PCA was used to analyze the character of the dataset and the score plot is shown in Figure 5(a). In order to avoid the disturbance of the data about USA, after deleting them, we re-analyzed the data (Figure 5 (b)).

From Figure 5(a), we can see that the concentrations of PBDEs in breast milk from USA are significantly higher than those in other countries. The next high level appears in Canada. For Europe (Figure 5(b)), except

United Kingdom, the other countries belong to the group of Asian countries, which are at the low level of PBDEs in milk in the worldwide.

The works on PFOS and PFOA in breast milk is relatively scarce. So et al. collected human breast milks from Zhoushan, China to evaluate the health risks in infants associated with exposure to PFCs^[96]. PFOS and PFOA were detected in all samples and the concentrations ranged from 40–360 to 47–210 ng/L, respectively. The concentrations were not correlated with maternal age, weight and infant's weight. But significant relationships were found between rate of consumption of fishes and other PFCs concentrations.

Kärman et al. analyzed the PFCs in Swedish breast milk collected from 1996 to 2004 and found that five PFCs compounds could be detected^[97]. Thereinto, PFOS was detected in all samples. The average value was 1% of the corresponding concentrations in bloods

Figure 4 The box chart of PBDEs in breast milk from different countries.

and there is a linear relationship between these two groups of data. The number of samples that were detected PFOA was relatively small. PFOS and PFOA levels in composite milk samples unchanged between 1996 and 2004 with a total variation of 20% to 32% coefficients.

4 The concentrations of PBDEs in human tissues

Table 2 lists PBDEs in adipose tissue collected from Asia, Europe, and North America. Different countries showed different concentrations of PBDEs. The most important congeners BDE47 and 153 accounted for 43%

and 26.3% of the total of PBDEs, respectively.

The research of PBDE in human tissue is mainly focused in Japan and Singapore. From 1970s to 2004 (Table 2), the concentrations of PBDEs in adipose tissue in Japan increased from 0.023 ng/g to 8.39 ng/g with an exponent trend. The concentrations of PBDEs in tissue from Singapore were similar to those from Japan. But the main congener was BDE47 and BDE99, 100, 153, and 154 were lower than LOD^[100].

The levels of PBDEs in adipose tissue from European samples are comparable to those from Asia. But the ratio of BDE99 is higher and no obvious change was found with the temporal trend. The highest concentration in human tissue exists in USA. An investigation in 2003–2004 showed that the concentrations of PBDEs in this country were 2 orders of magnitude higher than those in Europe and Asia. The average value is 399 ng/g, which is 10-fold higher than that in 1990s, and the highest is even up to 9639 ng/g. This suggested that individual concentrations are highly correlated with the occupational and exposure environment.

5 The relationship between the concentrations of PBDEs and PFOS and exposure environment

The concentrations of PBDEs and PFCs in human body are obviously related to the ambient environment. Many studies reported that the pollutant contents in bloods and human milk from exposure inhabitants were significantly higher than those of controlled people. Qu

Figure 5 PCA results of the concentrations in breast milk from different countries. (a) For component 1, the loading values of BDE47, 99, 100, 153, and 154 are 0.964, 0.983, 0.957, 0.217, 0.979, respectively; for component 2, the corresponding values are 0.253, 0.183, 0.285, 0.975, and 0.171; (b) the result excluding the data of USA. For component 1, the loading values are: 0.910, 0.938, 0.907, 0.701, and 0.327; for component 2, the corresponding values are 0.283, 0.286, 0.372, 0.384, and 0.937.

Table 2 PBDEs concentrations in adipose tissue from different countries (ng/g, lipid).

Country	Type	Date	No.	47	99	100	153	154	PBDE	Ref.
Japan	adipose	1970	10	0.017	0.004	0.002			0.023	[98]
Japan	adipose	2000	10	0.46	0.12	0.25	0.38	0.06	1.27	[98]
Japan	liver	2001	10	1.38	0.18	0.22	1.55	0.14	3.48	[34]
Japan	adipose	2003–2004	28	1.31	0.20	0.56	2.45	0.16	8.39	[99]
Singapore	adipose	2003–2004	16	2.89	n.d.	n.d.	n.d.	n.d.	3.63	[100]
Belgium	adipose	2000	20	1.45	0.28	0.48	2.49		4.70	[101]
Belgium	adipose	2001–2003	53	0.88	0.47	0.72	2.40	0.93	5.40	[101]
Sweden	adipose	1994	5	2.37	1.29	0.29	0.96	0.06	4.97	[102]
Sweden	adipose	1994	1	8.80	1.10	1.80	1.70		13.4	[103]
Finland	placenta	1996	11	0.77	0.41		0.40		1.58	[73]
Finland	adipose	1998	10	6.14	2.02		2.18		10.3	[104]
Finland	adipose		37	0.55	0.74	n.a.	0.30	n.a.	1.59	[105]
Spain	adipose	1998	13	1.36	0.42	0.51	1.83		4.12	[106]
Spain	adipose	2003	20	0.63	0.24	0.20	1.30	0.034	2.40	[107]
Czech Republic	adipose	2000	14	0.40	0.12	0.13	0.41	0.03	1.09	[108]
Czech Republic	adipose	2000	10	1.18	0.34	0.59	0.52	0.06	2.69	[108]
US	breast adipose	1996–1998	52	18.0	6.60	3.20	4.10	6.40	38.3	[109]
US	breast adipose	1997	22	18.3	6.59	3.17	4.09	6.40	38.6	[109]
US	adipose	2003–2004	52	132	74.4	67.7	91.8	8.30	399	[110]

No., The number of samples; n.d., not determined; n.a., not available.

et al. investigated the exposure to PBDEs among workers at an electronic waste dismantling region in Guangdong, China^[111]. The data showed that the concentrations of PBDEs in blood from occupational exposure workers were 10–20 times higher than those in the controlled group. BDE209 was the dominant congener and the highest was observed to be about 3436 ng/g (lipid), which was the highest concentration in human worldwide. Similarly, Thuresson et al. investigated the exposure to commercial deca-BDE in workers manufacturing or handling flame-retarded rubber^[112]. High concentrations of BDE209, nona-BDEs, and octa-BDEs were detected and relatively low concentrations of lower brominated congeners such as BDE47 and 100 were also found. The investigation also proved that the debromination of BDE209 exists in human body. Thuresson et al. followed up the concentrations change of PBDEs in e-waste dismantling worker before (1997) and after (2000) the improvement of working conditions^[113]. The study clearly showed that the industrial hygiene improvement could reduce the occupational exposure to higher brominated congeners. Although the amount of goods doubled in 2000 compared with 1997, a significant decrease in the serum levels of BDE183 and 209 was found. But the levels of BDE47 and BDE153 did not significantly change, which were thought to be longer half-lives (1.8 years and 6.5 years, respectively).

The pathway for the PBDEs in human body is a hotspot in current research. Wu studied the relationships

between the concentrations of PBDEs in human milk from Massachusetts, USA and data about personal characteristics, diet, home furniture, and electrical device, etc.^[17]. PBDEs concentrations were closely related to the concentrations in house dust, dietary habits, particularly the consumption of dairy products and meats, but not correlated with the consumption of fishes. Also, the PBDE levels in milk were positively correlated with the concentrations of PBDEs in house dust, which showed that indoor environment and diet both play important roles in human exposure to PBDEs even though the clear intake pathway into human body was not confirmed. There are also other evidence proving PBDE levels in pure vegetarians, which showed a decrease trend with the increase of ages^[114]. Meng et al. further compared the pathway of PBDEs into human body and revealed that the amounts of PBDEs by inhalation for infants were far higher than those for adult. In China, PBDEs in fishes for food and the consumptions of fishes were at a relatively low level in the world, while the amounts by inhalations were higher than those in other countries^[115].

For PFCs, food intake seems a prominent pathway into human body. Falandysz et al. proved that besides PFOS and PFOA, there were 8 PFCs compounds to be found to accumulate in human body by studying PFCs in human bloods from Baltic coast. Also, individuals who had a high fish intake contained the highest load of PFCs compared with other human subpopulations^[55].

6 Conclusions

As two kinds of emerging pollutants, PBDEs and PFCs have extensively spread in global environment and threatened the ecosystem. In the past, researchers spent lots of energy to study the environmental behaviors, transformation, transfer, toxicity etc. of these compounds. Many countries have made related policies and laws to restrict or prohibit the production and use of these two groups of compounds. For example, the uncertainties arising from the risk assessment and high level of uncertainty associated with potential risks make the European Union (EU) ban the use of penta-BDE and octa-BDE. US-EPA also has established strict regulation to restrict the production and usage of PFCs. The environment risk assessment required further work about the

environmental behavior, transformation, and bioaccumulations/biomagnifications via food chain for PBDEs and PFCs. In China, the research about these two groups of compounds just begins. But in the last several years, the study level has advanced rapidly. Many laboratories including sanitation system have focused on emerging chemicals, especially for the risk assessment in special areas, for example, e-waste dismantling area. But up to now, people are not clear about the source, the transformation and transport, the environmental repair, and the potential risk assessment about these two groups of emerging chemicals. The work will estimate the release of the emerging chemicals to ambient environment and the consumption of these contaminants. And it will assess ecology damage and apply evidence to carry out regulation and laws for the government.

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