An investigation into predictors of the human body burden of polybrominated diphenyl ether flame retardants

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Thesis submitted for the degree of Doctor of Philosophy
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June 2017

Declaration

I declare that this thesis is my own work. I have correctly acknowledged the work of others, in accordance with University and Institute guidance on good academic conduct. No part of the material offered has been previously submitted for a degree or other qualification in this or any other university. For joint works, my independent contributions have been outlined in the appropriate co-authorship forms.

Signature 

Date **30**th June 2017

Abstract

Background

Polybrominated diphenyl ethers (PBDEs) are a class of brominated flame retardant, which has been widely used around the world to meet fire safety regulations for fabrics, furnishings, electronics and vehicles since the 1970s. During the life-cycle of the product, PBDEs leach out into indoor air and dust. From there they are transported into the wider environment, and bioaccumulate through food chains. The human body burden of PBDEs increased dramatically from the 1970s until the 1990s as a result of this wide use and their lipophilic and persistent character. In 2009, the Stockholm Convention to protect human health and the environment from persistent organic pollutants, added PBDEs to its list of chemicals for which production, import, export and use should be eliminated. However, the effects of such measures are slow to impact levels in human tissue. Furthermore, recovery and recycling of electronics is an additional newer source of exposure. Potential adverse human health effects of PBDE body burden include reproductive toxicity, neurotoxicity, endocrine activity, DNA damage and immune effects.

Aim

The aim of this study was to investigate human body burden of polybrominated diphenyl ether (PBDE) flame retardants, PBDE sources and exposure pathways. This was divided into three more specific objectives: (a) To measure current UK human body burdens of PBDE and their contributors, (b) To investigate concentrations of PBDEs in UK diets and influencing factors, and (c) To investigate concentrations of PBDEs in UK indoor dusts and influencing factors.

Thesis Summary

This doctoral thesis by published works presents four articles that addressed those objectives, investigating current dietary and indoor environment exposure sources and pathways that lead to human PBDE body burden. The study centred on a cross-sectional cohort in the North East of England. A short pre-screening questionnaire identified volunteers who could be expected to provide a divergent range of exposures. The study recruited individuals to potentially reflect low, medium and high levels of exposure to PBDEs, such as oily fish eaters and vegetarians, and those

with possible occupational exposure. 20 study participants were selected: 10 cohabiting couples (10 males and 10 females) aged 26-43 years, living in the North East of England. Samples of matched serum, human milk, 24 hour duplicate diet and indoor dust from living areas, bedrooms, vehicles and workplaces were collected and anthropometric measurements taken. Seven day food and activity diaries, food frequency and lifestyle exposure questionnaires and room surveys were also completed.

The first article presents the findings of a systematic review into the relationships between diet and indoor environment exposure and human body burden to PBDEs.

The second article presents concentrations of PBDE and polybrominated biphenyl in participants' serum and milk. It also compares the current findings with global concentrations and previous UK measurements taken prior to EU use restrictions. A risk assessment for infant intake of PBDE via milk is included. Relationships between anthropometric information and body burden are explored.

The next article presents concentrations of PBDEs (and a range of other persistent organic pollutants (POPs) of interest) measured in 24 hour duplicate diet samples. These measurements are compared with estimations of adult dietary exposure derived from the Food Standards Agency's Total Diet Study 2011/12. Strengths and weaknesses of both methods were explored. Both sets of findings were then compared with previous UK dietary exposure estimates as well as estimates from around the globe. Temporal changes in dietary exposure to the POPs were explored.

The final article presents the concentrations of PBDEs in the indoor dusts for the cohort and findings from the room surveys, diaries and questionnaires. Together with the body burden and duplicate diet exposure findings previously presented, the influence of diet, indoor environments, behaviour and anthropometrics on the PBDE body burdens of the cohort are explored. Based on these findings, recommendations for reducing PBDE body burden are made.

For each article I discuss its contribution to the literature and a critique of the method. To close I reflect on my individual contribution to each article.

Acknowledgements

This research presented in this thesis has been conducted in collaboration with several organisations and individuals to which I am indebted for their assistance and support. In particular, I would like to thank my academic supervisors Professor Tanja Pless-Mulloli, Professor Judith Rankin, Dr Svetlana Glinianaia, Dr Martin Rose, Dr Alwyn Fernandes, Professor Stuart Harrad and Dr Susan Hodgson for their support, patience and friendship during the preparation of this submission.

I would also like to extend thanks to my co-authors Dr David Mortimer, Dr Mohamed Abou-Elwafa Abdallah and Dr Cassie Rauert for their expert guidance in exposure science, and to my annual assessors Professor Faith Williams Dr Laurence Castle for their helpful feedback and advice.

Perhaps most importantly, I must thank the amazing participants who gave up their time, opened up their homes to me, carried around buckets full of food, fasted and gave tissue samples, all in good humour and with great patience.

I'd like to thank Jan Gebbie and the wonderful nurses and staff at the Royal Victoria Infirmary's Clinical Research Facility for taking such good care of my valiant participants.

For their guidance and kindness during my analytical placement at the Food and Environment Research Agency I would like to thank Liz Greene, Margaret Miller, Melanie Holland, Klaas Harmannij, Frankie Smith, Joe Holland and Steve Petch. For finding my boutique accommodation whilst in on this placement I would like to thank Naseem Pervez.

For their guidance and support during analytical placements at Birmingham University and afterwards I would like to thank Dr Emma Goosey, Marian Jordan and Patsy and Colin Turner.

I would also like to thank Dr Aileen Mill, Dr Rute Vieira, Vicky Ryan and Dr Simon Kometa for statistical support, Ruth Wood for developing the questionnaire database and everyone I have shared an office with over the period for sharing the successes and softening the disappointments.

Finally, special thanks must go to my parents for encouraging my curiosity and resolve, and my very special thanks to my partner, Paul, for his loving support, infinite patience and at least 10,000 cups of tea during this epoch.

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Bramwell, L., Glinianaia, S.V., Rankin, J., Rose, M., Fernandes, A., Harrad, S. and Pless-Mulolli, T. (2016) 'Associations between human exposure to polybrominated diphenyl ether flame retardants via diet and indoor dust, and internal dose: A systematic review', *Environment International*, 92–93, pp. 680-694.

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Abbreviations and Glossary

$\sum$BDE$_{3\text{-}7}$	Sum of PBDEs with 3 to 7 bromines aka sum of tri to hepta bromines
µg	Microgram (1×10^{-6} of a gram)
ATSDR	Agency for Toxic Substances and Disease Registry - a federal public health agency of the U.S. Department of Health and Human Services
BFR	Brominated flame retardants
BGS	British Geological Survey
BMDL$_{10}$	Benchmark doses (BMDs) are critical health endpoints e.g. neurodevelopmental effects. BMDL$_{10}$ indicates a 10% response at the referred to dose.
BMI	Body mass index = weight (kg)/height^2 (m^2)
bw	Body weight, although we had actual body weights for our participants many studies use either 60 or 70 kg as an approximate for their participants.
COT	The UK's Committee on Toxicity of Chemicals in Food, Consumer Products and the Environment is an independent scientific committee that provides advice to the Food Standards Agency, the Department of Health and other Government Departments and Agencies on matters concerning the toxicity of chemicals.
DD	Duplicate diet - participants place the same amount of food (and sometimes drink) in a receptacle to provide a copy of their diet for the time period of the assessment
Deca BDE	The overarching term for PBDE products with BDE-209 as the main constituent
decaBDE	BDE-209, the fully substituted PBDE having ten bromines
EFSA	European Food Safety Authority
Fera	Food and Environment Research Agency (now Fera Science Ltd.)

FSA	Food Standard Agency
g	gram - a metric unit of mass equal to one thousandth of a kilogram
genotoxic	may damage DNA
HBCD	Hexabromocyclododecane
HBLV	Health based limit value
Homologue	Group of congeners having the same number of Br atoms
IHS	Institute of Health & Society
IRAS	Integrated research application system
IUPAC	International Union of Pure and Applied Chemistry
kg	kilogram $1x10^3$ grams
LB	lower bound data, measurements below the LOD or LOQ are given a value of 0 in statistical summaries
LOAEL	lowest observable effects levels
LOD	Limit of detection
Log Kow	Kow = Concentration in Octanol/ Concentration in water.
lw	Lipid weight, aka fat weight, lipophilic analyte concentrations in biological samples are often expressed this way
MB	median bound data, measurements below the LOD or LOQ are given a value of 0.5*LOD or 0.5*LOQ in statistical summaries
MOE	Margin of exposure
NABS	Newcastle Allotments Biomonitoring Study
NCC	Newcastle City Council
NERC	Natural Environment Research Council
ng	Nanogram (1×10^{-9} of a gram)

NHANES The National Health and Nutrition Examination Survey, a program of studies designed to assess the health and nutritional status of adults and children in the United States.

Octa BDE The overarching term for PBDE products with BDE-183 as the main constituent

octaBDE The homologue of PBDEs with 8 bromines substituted around the two phenyl rings

P Vapour pressure

P90 90th Percentile, 90% of measurements are within this value

P97.5 97.5th Percentile, 97.5% of measurements are within this value

PAH Polyaromatic hydrocarbons

PBB Polybrominated biphenyls

PBDD/F Polybromobenzodioxins and polybromodibenzofurans, also known as brominated dioxins (PBDDs) and brominated furans (PBDFs)

PBDD/F/PBB Brominated dioxins and dioxin like compounds

PBDE Polybrominated diphenyl ether

PCBs Polychlorinated biphenyl

PCDD/F polychlorobenzodioxins and polychlorodibenzofurans, also known as chlorinated dioxins (PCDDs) and chlorinated furans (PCDFs)

Penta BDE The overarching term for PBDE products with BDE-47, -99, as the main constituent

pentaBDEs The homologue of PBDEs with five bromines substituted around the two phenyl rings

pg Picogram (1×10^{-12} of a gram)

PI Principle Investigator

POP Persistent organic pollutant

PUF Polyurethane foam

RfD Reference dose

RIVM The Dutch National Institute for Public Health and the Environment

SVOC semi-volatile organic compounds

T3 Triiodothyronine

T4 Thyroxine

TDS Total diet study

TFP Tyne Fish Project

UB Upper bound data, measurements below the LOD or LOQ are given a value of 1*LOD or 1*LOQ in statistical summaries

UK United Kingdom

US-EPA The Environmental Protection Agency of the USA

WHO 1998 -TEQ WHO Toxic equivalences set by the World Health Organisation in 1998

WHO 2005 -TEQ WHO Toxic equivalences set by the World Health Organisation in 2005

XRF X-ray fluorescence (spectroscopy)

Context

My primary background is in analytical chemistry, environmental biogeochemistry and contaminated land risk assessment. When I began work at the School of Population and Health Sciences (now the Institute of Health & Society, IHS) in 2005, it was with two roles; to assess Environmental Permit Applications' public health risks for high risk category industrial processes and to investigate contamination on allotment gardens for Newcastle City Council (NCC). As the allotment investigations progressed we uncovered as many questions as answers and I began to apply for funding to address these. It became apparent that unless I had a PhD these applications would always fall short. At the same time, the Environment and Health Team, within which I worked at IHS, was involved in an investigation of PBDE flame retardants in house dust and I was developing a keen interest in emerging contaminants and indoor and dietary pollutants.

Health concerns regarding Penta- and Octa BDE brominated flame retardant products meant they had recently at that time (2004) had use and import restrictions placed on them in the EU and were being voluntarily phased out in the USA. Then some astonishingly high concentrations of the brominated flame retardant BDE-209 were measured in UK dusts by a group at the University of Birmingham. These high UK measurements were attributed to the UK's more stringent fire safety regulations requiring more flame retardant product to be used. BDE-209 was promoted as safer compared to Penta- and Octa BDE, but at such high exposure levels was it really safe? What about more toxic breakdown products? New technological advances in laboratory analysis at the UK's Food and Environment Research Agency (Fera) (now Fera Science Ltd.) meant that reliable measurements of BDE-209 in biological samples were becoming possible. Given the absolute ubiquity of polybrominated diphenyl ethers (PBDEs) in all indoor environments and their propensity to adsorb to surfaces, the precautions required to avoid contamination of samples as well as the complex extraction procedures required made these analyses almost prohibitively expensive. I wondered if it was possible to determine the level of PBDE in room dust simply by conducting a room contents and use survey, and could PBDE dietary exposure be estimated by a questionnaire? Some clear research questions were emerging to me.

The need for an holistic approach to persistent organic pollutants (POPs) investigation and modelling was evident and the timing for an investigation into UK human body burden of PBDEs with matched diet and indoor dust samples was perfect. Natural Environment Research Council (NERC) Case Studentship funding was secured and so this PhD investigation began. Research training and fieldwork was based at Newcastle University's IHS. The University of Birmingham's Division of Environmental Health and Risk Management provided training in monitoring and sampling of indoor environments as well as equipment and expertise for analysis of the dust samples for POPs. Fera provided technical training in dietary assessment studies and analytical chemistry techniques for biological samples.

As a side note I am pleased to be able to report that fortunes with the allotment investigations research funding changed in due course and key elements of the investigation (Newcastle Allotments Biomonitoring Study, NABS) have now been successfully undertaken. During my work with NCC, we had found consistently high concentrations of lead in allotment garden soils, at levels of about 10 times the critical values recommended by the UK Environment Agency. British Geological Survey (BGS) data indicated that urban soils across the UK were in line with these concentrations. During the period 2004 to 2010, NCC measured fruit and vegetable uptake of lead and soil lead bioaccessibility on allotments. We found both to be low and considered the physical and mental health benefits of allotment garden to outweigh any small health risk concern. Working with an expert steering group NCC elected to keep the allotment sites open. We were concerned that other local authorities may be closing similar sites down. It was vital to establish whether the raised lead levels in soil were leading to blood lead levels that were a concern to health. Funding from the Institute of Sustainability and Institute of Social Renewal at Newcastle University allowed us to measure lead concentrations in the blood of allotment gardeners and their non-gardening friends and neighbours, at the same time as investigating the wide range of confounders that also affect blood lead levels. I was the principle investigator (PI) for this study (2015 to present). I disseminated the findings via public engagement meetings, contaminated land sector and exposure science conferences. Examples of conference abstracts and posters for this research project are presented in Appendix D. Journal articles covering the relationship between allotment soil lead concentrations and the blood lead

concentration of gardeners, the solid phase partitioning and bioaccessibility of the soil lead and vegetable uptake of lead in soils with corresponding lead from diet exposure estimates will be published in due course.

Newcastle upon Tyne and its surrounding areas' rich industrial history has produced a wide range of contaminants, affecting soil and water courses. The UK Food Standard Agency (FSA) funded an investigation of contaminants in fish caught in the River Tyne, to investigate potential health risk for persons eating Tyne river fish. I was also the PI for this study (2008-9), disseminating findings at conferences on river sediment and POPs. Examples of conference abstracts and posters for this are presented in Appendix D. A journal article covering concentrations of metals, polyaromatic hydrocarbons (PAHs), polychlorobenzodioxins and polychlorodibenzofurans (PCDD/Fs), polychlorinated biphenyl (PCBs), PBDEs and Hexabromocyclododecane (HBCD) in different fish species and sample types from the Tyne river estuary, UK, with dietary intake estimates and public health advice for anglers will be published in due course.

Chapter 1 Research Setting

1.1 Thesis overview

This thesis is presented in three main sections:

1) An introduction to polybrominated diphenyl ethers (PBDEs) containing essential information that has helped me interpret the study findings throughout its development and a summary of the study aims and hypotheses.
2) The main body of the study findings presented as four published papers with some additional comments on context.
3) An overarching discussion of the PhD, findings and implications for health and policy.

1.2 PBDE history, sources, regulation

1.2.1 Mode of operation and chemical structure

PBDEs are a class of brominated flame retardant, which have been widely added to resins and polymers since the 1970s, in order to meet fire safety regulations for fabrics, furnishings, electronics and vehicles. PBDEs work by slowing the rate of ignition and fire growth in petroleum based polymers and resins. As the PBDE heats up bromine atoms are released smothering the flame by pushing away the oxygen required to feed it. PBDEs are additive flame retardants, meaning that they are mixed into plastics or foam polymers without forming chemical bonds. The lack of chemical bond with the product allows PBDEs to leach out of the product and accumulate in the environment.

PBDE molecules are made up of two phenyl rings joined by an ether bond. They can have between 1 and 10 bromines around the rings (see *Figure 1*). There are 209 potential PBDE structures, known as congeners, named with the same International Union of Pure and Applied Chemistry (IUPAC) numbering system as PCBs. Congeners with the same number of bromines are known as homologue groups.

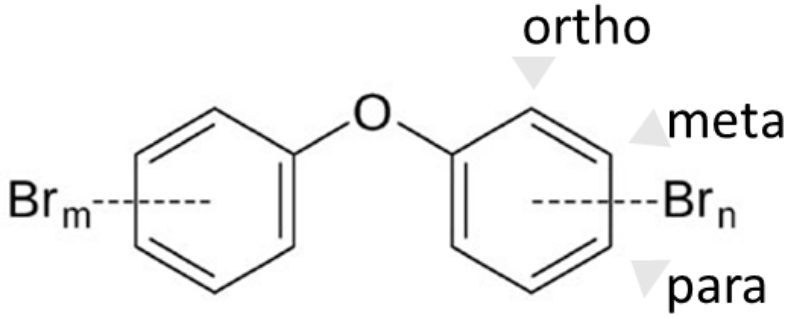

Figure 1 Basic Molecular structure of PBDE (m + n = 1 to 10), showing ortho, meta and para substitution positions, created in ChemDraw

1.2.2 **Commercial products**

There are three commercially produced mixtures of PBDEs that have been extensively used around the world: (1) Penta BDE (major congener components having five bromines: BDEs -47, -99 and -100), (2) Octa BDE (BDE-153 and BDE-209), and (3) Deca BDE (BDE-209 having 10 bromines) (La Guardia et al, 2006). A summary of production volumes in 2000 (more up to date information is not available) and potential uses of widely used PBDEs is provided in *Table 1*. The percentage weight of congeners making up a selection of the commercial PBDE mixes is presented in *Table 2*.

Items containing flame retardant chemicals are simply labelled as meeting fire regulations. No information is given on the chemicals used to meet these requirements, either on the products or in the manufacturer's literature, and flame retardant manufacturers do not make the chemical content of their products publicly available.

Table 1 Global annual production of polymers in 2000 and their BFR uses

Commercial PBDE product	Annual polymer production in 2000 (tonnes per year)[1,2]	Polymer[3]	Examples of potential products[4]	Flame retardant content (%)
Penta BDE	150	Polyurethane foam (PUF) (95% of Penta BDE use[4])	Vehicle foams in seats and head rests; domestic soft furnishings such as mattresses, cot mattresses, sofas; domestic and office padded chairs; foam safety blocks in sports for gymnastics practice; foam-based packaging[3]	3-30[6,7]
Octa BDE	50	Acrylonitrile-butadiene-styrene copolymer (ABS) (95% of use[8]) at 12-18% w/w content); High Impact Polystyrene (HIPS); Polybutylene terephthalate (PBT); Polyamide polymers (nylons); Low density polyethylene (LDPE), Polycarbonate (PC)	Office and business appliance housings (ABS); instrument control knobs (HIPS); Car components such as gear housings (PBT); electrical insulators, switch housings, cable ties, power tool housings (nylons)[9]	12-18% w/w
Deca BDE	350	High Impact Polystyrene (HIPS)	TV and computer monitor housings, cables, circuit boards	11-15[10]
	200	Polyamides (nylons)	Nylons and Kevlar, carpets, plastics for cars	13-16
	200	Polyolefins (polypropylene and polyethylene)	Shrink film, blow or injection moulded bottles and syringes	42952
			Fabrics and textiles can also be treated with PBDE commercial mixtures to provide protection.	5-30[11]

Notes: [1] Alaee et al., 2003, [2]Arias, 2001, [3]EFSA, 2011 [4]BPF, 2017, [6] Hale et al., 2002, [7] Stapleton et al., 2009, [8]E.C., 2003, [9]Palmer, 2002, [10]Allen et al., 2008, [11]Hooper et al., 2000 (Hooper and McDonald, 2000; Arias, 2001; Hale *et al.*, 2002; EC, 2003; Allen *et al.*, 2008; Stapleton *et al.*, 2009; EFSA, 2011; BPF, 2017)

Table 2. Summary of major PBDE components (%w/w) in Commercial PBDE mixes as determined by La Guardia (2006).

PBDE congener	Technical PBDE products					
	Penta BDE		Octa BDE		Deca BDE	
	USA	EU	USA	EU	USA	EU
	DE-71	Bromkal 70-5DE	DE-79	Bromkal 79-8DE	Saytex 102E	Bromkal 82ODE
BDE-17	0.07	0.05	nd	nd	nd	nd
BDE-28/33	0.25	0.1	nd	nd	nd	nd
BDE-49	0.74	0.36	nd	nd	nd	nd
BDE-47	38.2	42.8	nd	nd	nd	nd
BDE-68/42	0.53	0.21	nd	nd	nd	nd
BDE-100	13.1	7.82	nd	nd	nd	nd
BDE-99	48.6	44.8	nd	nd	nd	nd
BDE-85	2.96	2.16	nd	nd	nd	nd
BDE-126/155	0.21	0.67	nd	nd	nd	nd
BDE-138	nd	nd	0.62	nd	nd	nd
BDE-153	5.44	5.32	8.66	0.15	nd	nd
BDE-154	4.54	2.68	1.07	0.04	nd	nd
BDE-171	nd	nd	1.81	0.17	nd	nd
BDE-183	nd	nd	42	12.6	nd	nd
BDE-196	nd	nd	10.5	3.12	nd	0.46
BDE-197	nd	nd	22.2	10.5	nd	0.03
BDE-203	nd	nd	4.4	8.14	nd	nd
BDE-206	nd	nd	1.38	7.66	2.19	5.13
BDE-207	nd	nd	11.5	11.2	0.24	4.1
BDE-209	nd	nd	1.31	49.6	96.8	91.6

Notes: nd - not detected, Cell shading demonstrates the relative proportion of the congener making up the technical mix.

Historically, the UK was the fourth largest producer of PBDEs in the world, with an approximate annual output of 25,000 metric tonnes (Alaee *et al.*, 2003a). Penta and Octa BDEs were used in the greatest amounts in North America, where flame retardant regulations, in particular California (Shaw *et al.*, 2010), required use of greater amounts of flame retardant chemicals as the polyurethane foam (PUF) of soft furnishings were treated rather than the fabric covers (Technical Bulletin 117). This has resulted in North American body burdens of these congeners one to two orders of magnitude higher than those found elsewhere in the developed world (Hites, 2004;

Frederiksen *et al.*, 2009; Shaw *et al.*, 2010). Concentrations of BDE-209 are considerably higher in UK indoor dusts than in dusts from mainland Europe (Harrad *et al.*, 2008c; Frederiksen *et al.*, 2009), again a result of more stringent fire safety regulations (Furniture and Furnishings Fire Safety Regulations 1988/1989, 1993 and 2010).

1.2.3 Use restrictions

Penta and Octa BDE commercial products were effectively banned from use in the EU and voluntarily phased out in the USA from 2004 (EC, 2003). Deca BDE has been restricted from use in electrics and electronics in the EU since 2008 (EC, 2008). Voluntary phase out of Deca BDE from use as a flame retardant fabric coating in the UK took place around 2012. *Table 3* provides a timeline of some important PBDE publications and regulations demonstrating mounting concerns for their effect on human health and environment. In 2009 Penta and Octa BDE were added to the list of POPs for elimination in the Stockholm Convention, an international environmental treaty, with the aim of eliminating production, use and unintentional release in signatory countries.

Table 3 PBDE Timeline of some exposure findings and regulations

Year	Discovery, usage and regulation
1987	PBDEs are detected in fish consuming birds and marine mammals in the Baltic Sea, North Sea and Arctic Ocean (Jansson *et al.*, 1987).
1998	Exponential rise in Penta BDE in Swedish breast milk from 1972 – 1997 is discovered (Meironyte *et al.*, 1999).
2001	Estimated global demand for PBDE is 67,440 (BSEF, 2007). The use of Penta BDE was voluntarily withdrawn from the Japanese market (Watanabe and Sakai, 2001).
2004	Penta and Octa BDE were banned from all uses in the EU market (EC, 2003) and phased out in USA. Great Lakes Chemical Corporation (now Chemtura Corporation) the US producer of Penta and Octa BDE voluntarily ceased production. The Voluntary Emissions Control Action Programme (VECAP) was introduced to manage, monitor and minimise industrial emissions of Deca BDE to the environment (VECAP, 2004)
2006	Deca BDE was listed as 'toxic substance' under the Canadian Environmental Protection Act (CEPA). Sweden restricted use of Deca BDE in textiles furniture and cables. In the USA, Maine and Washington States USA banned Deca BDE in mattresses and furniture.
2007	The European Regulation for the Registration, Evaluation, Authorisation and Restriction of Chemical Substances (REACH) came into force. Deca BDE is registered with REACH.
2008	Deca BDE was banned from use in electronics and electrical applications for the EU market. Norway bans production, import, export use and placing on the market of Deca BDE and products containing 0.1% Deca BDE in textiles, furniture and insulation, except in the transport sector. Chinese and Korean regulations allow Deca BDE in Electronic equipment. US-EPA publishes RfDs for PBDEs (US-EPA, 2014)
2009	Penta and Octa BDE are added to the Stockholm Convention's list of POPs for elimination.
2011	EFSA publishes $BMDL_{10}$ for BDEs-47,-99,-153 and -209 (EFSA, 2011).
2012	Use of Deca BDE on fabrics is phased out in UK (White, 2013).
2017	UK, DEFRA consultation on implementation of the Stockholm Convention for PBDEs.

1.3 Chemical characteristics of PBDEs

Chemical characteristics of some more commonly discussed PBDEs are presented in Table *4* and their relevance for interpreting pollution pathways discussed below.

1.3.1 Volatility – Vapour pressure (P)

In general, PBDEs have low volatility and the lower the degree of bromination, the smaller the molecule, the more readily it will partition to air (P increases). In addition, ortho substituted PBDEs tend to have higher P (Wong *et al.*, 2001) relative to their homologue group. Vapour pressure (P) is the equilibrium of a molecule between solid (or liquid) state and gaseous state at a specified temperature. P can indicate whether a molecule is likely to be in vapour phase or adsorbed to particulate matter (Eisenreich *et al.*, 1981). This is key when assessing PBDEs emission from consumer products, release and adhesion to PUF and dust particles, and environmental fate. Penta BDEs are semi-volatile organic compounds (SVOCs), slowly volatilising out of treated products (Weschler and Nazaroff, 2008). Their rate of volatilisation increases as products containing PBDEs heat up, a common occurrence for electronics during use and vehicles. Deca BDE has a high relative molecular mass (959.2 g/mole) and is almost non-volatile at room temperature.

1.3.2 Environmental release and transport

PBDEs make their way into the wider environment during their manufacture, treatment of products, everyday use of products containing PBDEs, disposal of domestic cleaning waste (such as floor and clothes washings) into the waste water system, landfill waste, waste combustion or recycling practices with subsequent use of new products. They leach out of the treated products into indoor dusts and air through use and volatilisation (Sjodin *et al.*, 2003; Rauert and Harrad, 2015) where they are now ubiquitous (Harrad *et al.*, 2010). From indoor environments, they migrate further into the wider environment (Harrad and Diamond, 2006).

PBDEs travel long distances in the atmosphere bound to fine particles or in vapour form, transported by weather conditions. Tiny fragments of PUF could also diffuse into the atmosphere (Hale *et al.*, 2002). Rain, snow and gravity bring these to

ground, either to be further transported in the atmosphere, bind to soils or move into water courses binding to sediments which act as environmental sinks until re-suspended by storm events. Sewage sludge addition to agricultural land is another route that indoor PBDEs move into the environment (Rhind *et al*, 2013; Venkatesan and Halden, 2014). Grazing animals may be exposed to PBDEs adsorbed to soils (Hombach-Klonisch *et al*, 2013; Evans *et al*, 2014). Even though PBDEs are relatively stable, they are susceptible to photolytic debromination when they are exposed to ultraviolet light (US-EPA, 2010). This can result in smaller, more bioaccessible congeners.

1.3.3 Octanol Water Partition Coefficient (K_{ow}), aqueous solubility (S_w) and associated behaviour in the environment

PBDEs are highly lipophilic and hydrophobic compounds. This characteristic is demonstrated by their high log K_{ow}s (5-12) which increase with increased degree of bromination (see Table *4*). K_{ow} is the ratio of a chemical's concentration in the aqueous and octanol phases of a two phase system; i.e.

$$K_{ow} = \text{Concentration in octanol phase / Concentration in aqueous phase}$$

As the K_{ow} for organic chemicals range over ten orders of magnitude they are usually expressed as log K_{ow}. A substance's log K_{ow} can be used to estimate its water solubility (S_w), soil and sediment adsorption and bioconcentration factors, making it particularly useful information in the study of historic and emerging POPs. Log K_{ow} values are inversely related to S_w and proportional to a substance's molecular weight. Log K_{ow} indicates the relative tendency of an organic compound to adsorb to soil and living organisms. Very high log K_{ow} values (>4.5) indicate potential to bio-accumulate in living organisms.

PBDEs' S_ws decrease with higher bromination. Aqueous solubility (S_w) is directly related to environmental mobility. Substances with low S_w, low P and high log K_{ow} values such as PBDEs, preferentially adsorb to organic matter in soils, sediments or particles because of their low affinity for water causing the soil or sediment to act as a sink for the substance (ATSDR, 2004; D'Silva *et al.*, 2004). Conversely, substances with high S_w are quickly distributed in the environment in the hydrogeological cycle (Boethling and Mackay, 2000).

Examples of estimated environmental half-lives of PBDEs are 29, 140 and 476 days for penta, octa and deca BDEs respectively in air (for a photolysis endpoint) (Meylan and Howard, 1993) and 6 to 50 years for Deca BDE in sediment (Tokarz *et al.*, 2008). Smaller, less brominated PBDEs have lower K_{ow}s and these can be expected to have environmental half-lives of up to several years in sediment (Tokarz *et al.*, 2008).

Table 4. Chemical characteristics of some common PBDEs

IUPAC Nomenclature	IUPAC full chemical name	molecular weight (g/mole)	Vapour pressure (Pa)c	Log K_{ow}	Half Life in Human Serum	USEPA Reference Dose (ng/kg bw/day)	EFSA $BMDL_{10}$ (ng/kg bw/day)
BDE-28	2,4,4′-tri-BDE	406.9	2.32×10^{-3}	5.94 ± 0.15[a]			
BDE-47	2,2′,4,4′-tetra-BDE	485.8	4.19 x 10-6	6.81 ± 0.08[a]	3 years [d]	100	172
BDE-99	2,2′,4,4′,5-penta-BDE	564.7	2.46 x 10-7	7.32 ± 0.14[a]	5.4 years [d]	100	4.2
BDE-100	2,2′,4,4′,6-penta-BDE	564.7	9.57 x 10-7	7.24 ± 0.16[a]	2.9 years [d]		
BDE-153	2,2′,4,4′,5,5′-hexaBDE	643.6	1.35 x 10-8	7.90 ± 0.14[a]	11.7 years [d]	200	9.6
BDE-154	2,2′,4,4′,5,6′-hexaBDE	643.6	5.64 x 10-8	7.82 ± 0.16[a]	5.8 years [d]		
BDE-183	2,2′,3,4,4′,5′,6-heptaBDE	722.5	2.69 x 10-9	8.27 ± 0.26[a]		3000	
BDE-203	2,2′,3,4,4′,5,5′,6-octaBDE	801.4			37-91 days [e]		
BDE-209	2,2′,3,3′,4,4′,5,5′,6,6′-decaBDE	959.2	1.64 x 10-12	nr[a] 12.11[b]	11-18 days [e]	7000	1,700,000

Notes: [a]Braekevelt *et al.* (2003), [b]ECB (2001) [c]EFSA (2011), [d]Geyer et al. (2004), [e]Thuresson et al (2006); vapour pressure (P) = volatility decreases with size of molecule *i.e.* number of bromines, Log Kow = octanol-water partitioning coefficient increases with number of bromines, IUPAC Nomenclature (Ballschmiter and Zell, 1980)

1.3.4 **Bioaccessibility & Bioavailability**

In general, the larger the PBDE molecule (*i.e.* the more bromines there are) the less bioaccessible it is. The bioaccessible fraction of a substance is the fraction released from the ingested matrix in the gastrointestinal tract becoming available for absorption (Heaney, 2001) whereas the bioavailable fraction reaches systemic circulation for use by the target tissue (Wood, 2005). The bioaccessibility of ingested PBDEs in humans has been estimated to be 32-60% for tri- to hepta-BDEs, and 14-25% for Deca BDE, with PBDE bioaccessibility generally decreasing with increasing bromination, molecular size and log K_{ow} (Abdallah *et al.*, 2012; Fang and Stapleton, 2014).

1.3.5 **Environmental bioaccumulation**

The chemical characteristics such as thermal stability and the lipophilic nature of PBDE causes them to accumulate in fatty tissue and bioaccumulate up food chains (Qin *et al.*; Darnerud *et al.*, 2001; Vetter and Jun, 2003). Freshwater and marine food webs biomagnify PBDEs from sediment through to fish and higher predators. On land agricultural livestock feed on crops, grains and grasses picking up PBDEs on soil particles as well as PBDEs taken up into plants or deposited on their outer leaves.

The Stockholm Convention's criteria for listing for bioaccumulation is a log K_{ow} value >5. Molecules with molecular weight above 700 g/mol e.g. octa to deca BDEs, have greater difficulty passing through cell walls. As such, the less brominated congeners of PBDE tend to bioaccumulate more than higher brominated congeners (ATSDR, 2004). Bioaccumulation is when the biological sequestering of a substance by an organism - via either respiration, ingestion or dermal contact, takes place at a greater rate than excretion of the substance, resulting in the organism having a higher concentration of the substance than that in its surrounding environment. The more hydrophobic/ lipophilic a substance is (the higher the K_{ow}) the more likely it is to bioaccumulate in organisms.

The environmental persistence and wide usage of PBDEs have led them to permeate environments and food chains around the world. PBDEs have been measured in polar bears and penguins, sewage sludge, soils and river and lake

sediments (Allchin *et al.*, 1999; De Boer *et al.*, 2003; Muir *et al.*, 2006; Eljarrat *et al.*, 2008; Harrad *et al.*, 2009; Law *et al.*, 2014; Mwangi *et al.*, 2016).

1.3.6 **Human half life**

It is widely accepted that PBDEs can have substantial half-lives in humans. There is a general trend of shorter half-lives and lower bioaccessibility for the higher brominated compounds with estimates of residence time for BDE-209 of just a few days and for main congeners of the technical Penta BDE mixture (i.e. BDE-47, -99, -100) around two to four years (Geyer *et al.*, 2004; Thuresson *et al.*, 2006). Recent evidence in humans and peregrine falcon eggs suggests that BDE-209 which has limited human bioaccessibility, short human half-life and a high EFSA $BMDL_{10}$ may undergo metabolic debromination to BDE-153 which has greater human bioaccessibility, a long human half-life ATSDR and much lower EFSA $BMDL_{10}$ (see Table 4.) (Roberts et al., 2011; Abdallah and Harrad, 2014).

1.4 Human exposure to PBDEs

Biomagnification of PBDEs in food chains, where these lipophilic molecules are concentrated in animal and marine fats, results in diet being a major route of exposure to PBDE for humans, especially those who consume large amounts of animal products (Harrad and Diamond, 2006). Oily fish, red meat and dairy products are recognised to be major dietary sources of PBDEs (Domingo, 2004; Harrad *et al.*, 2004; Schecter *et al.*, 2006; Domingo *et al.*, 2008). Food may also potentially be contaminated with PBDEs during processing. Diet was always assumed to be the only significant non-occupational exposure pathway – the same as that for historic POPs such as PCBs, polychlorinated dibenzodioxins and polychlorinated dibenzofurans (PCDD/Fs). However, human PBDE body burdens in the USA were a magnitude higher when compared with those in Europe whilst PBDE concentrations in foods were much closer than that data would suggest if food was the only source of exposure. So, unlike PCBs and PCDD/F, PBDEs in indoor dust were found to have an important role in human exposure (Rudel *et al.*, 2003; Stapleton *et al.*, 2005). This can explain, to some extent, the wide variation seen in human body burdens (Jones-Otazo *et al.*, 2005; Fischer *et al.*, 2006; Harrad *et al.*, 2006; Sjodin *et al.*, 2008).

Human PBDE exposure begins with transfer from mother to fetus during pregnancy and further transfer occurs during breastfeeding (Guvenius et al., 2003; Carrizo *et al.*, 2007; Rose *et al.*, 2010). Infant intake of PBDEs from both diet and dust is greater per kg body weight than that of adults. This is one reason why young children have higher body burdens than older children and adults. Infants greater intake of dust due to their frequent hand to mouth behaviours whilst spending lots of time on floors and carpets is thought to be another cause (Jones-Otazo *et al., 2005*; Fischer *et al.*, 2006; Lorber, 2008; Johnson-Restrepo and Kannan, 2009; Stapleton *et al.*, 2012).

PBDE concentrations in dust have wide variation and can only be ascertained by laboratory analysis of dust collected in that specific environment. Dust concentrations of PBDEs vary within rooms between flooring and raised surfaces, with distance from PBDE treated items and over time (Harrad *et al.*, 2008). Using counts of soft furnishings or electronics in a room gives either no or weak association

with PBDE concentrations as other flame retardant chemicals can also be used to treat these products (Stapleton *et al.*, 2004; Wu *et al.*, 2007). A hand held x-ray fluorescence (XRF) meter can be used to measure bromine content of items with which it makes contact, but this measurement cannot distinguish between PBDEs and other sources of bromine such as other BFRs and azo dyes (Peng *et al.*, 2016). XRF analysis will not pick up bromines from PBDEs used on the items such as printed circuit boards held inside solid casing but which still heat up an emit PBDEs during use. Collecting and analysing small samples from items containing flame retardants is the only way to identify their PBDE content, but this is rarely a practical means of assessing exposure. Even if we know the PBDE content of an item, the rate of emission of PBDEs will alter according to the chemical characteristics of the congeners, and conditions in the room such as temperature, ventilation and wear and tear of items.

PUF breaks down with age shedding particles containing PBDEs. Scanning electron microscopy and XRF have been used to identify small chips of PBDE containing plastics in samples of house dust (Webster *et al.*, 2009).

1.4.1 Measuring human body burden

Serum and breast milk are the most commonly used matrices for human biomonitoring of PBDEs. Serum has contact with the whole body and has an equilibrium with organs and adipose tissues where PBDE is stored. However, a relatively large sample of serum is required due to the low proportion of lipid in serum (usually <1% in healthy adults). Breast milk has a higher lipid content (~4-5%) but its relationship with body burden is more complex and the population for whom this is a potential matrix to sample is naturally limited. The USA has a national biomonitoring program, the National Health and Nutrition Examination Survey (NHANES), that measures PBDEs and many other potentially harmful compounds in the population aged 12 and over but the high cost of sample collection and analysis means such programs are limited elsewhere.

1.4.2 Health effects

Potential adverse human health effects of PBDE exposure and body burden are reproductive toxicity, neurotoxicity and immune effects (Darnerud *et al.*, 2001;

Meeker *et al.*, 2009; Gascon *et al.*, 2012; Eskenazi *et al.*, 2013). 'Possible evidence' for thyroid disorders, reproductive health effects, and neurobehavioral and developmental disorders has been reported in a recent systematic review of human health consequences of exposure to PBDEs (Kim *et al.*, 2014). Evidence of these effects has been seen in animal and in vitro research, where the mechanism appears to be altered hormone regulation (endocrine disruption) (Meerts *et al.*, 2000; Viberg *et al.*, 2006; Marchesini *et al.*, 2008; Linares *et al.*, 2015). Exposure during key developmental stages in infancy is most damaging as this is the time when altered hormone regulation will have the greatest impact. Unfortunately, this is also the period of greatest exposure and body burden. Octa BDE has been indicated as a potential teratogen (a substance that can cross the placenta and is considered a prenatal developmental toxin) (Darnerud *et al.*, 2001). Carcinogenic potential has been suggested for Deca BDE (US-EPA, 2010) although it is classified by the International agency for research on cancer (IARC) in Group 3 (Not classifiable as to its carcinogenicity to humans) The US-EPA gives all PBDEs the classification Group D (Group D: Not classifiable as to human carcinogenicity).

1.4.3 **Exposure assessment**

Human body burden of a substance of concern can often be estimated by measuring concentrations in serum, urine, breast milk, hair or even toenails, depending on the substances chemical characteristics. Exposure pathways are estimated using estimates of input such as exposure via dust, diet, soil or drinking water along with measurements of the substances concentrations in those media. Age, gender, genetics and lifestyle may all mediate uptake and metabolism or excretion of the substance. Sub populations, such as nursing infants and toddlers may have unique exposure routes and may be more susceptible to developmental health effects.

1.4.4 **Risk Characterisation**

Where risk is the probability of an adverse outcome, risk characterisation is the estimation of resulting adverse health effects for a given exposure scenario. It requires the integration of data from exposure and dose response assessments. For non-cancer effects, the actual level of exposure is compared with an estimated level

of exposure at which no adverse effects would be expected. No observable adverse effects levels (NOAELs) are usually derived from animal studies. A $NOAEL_{10}$ figure indicates that 10% of the tested population demonstrated the adverse health outcome under examination. Reference doses (RfD) are derived from NOAELs by dividing by factors to address uncertainties such as inter species extrapolation and human variability, and safety factors to provide an estimate of a dose which would not be expected to result in adverse health effects in humans. Margins of exposure (MOEs) are another tool used for risk assessment, usually where the substance may be both genotoxic and carcinogenic. The MOE is the ratio between the dose at which a small but measurable adverse effect is observed (e.g. $NOAEL_{10}$) and the exposure under consideration for the population under investigation. Benchmark dose levels (BMDLs) are used as points of departure (POD) for adverse health effects derived from dose response curves. An estimated 10% increase in incidence of an adverse effect would be the $BMDL_{10}$.

1.4.5 **Health Criteria Values**

The US-EPA published RfDs for major PBDEs in 2008 which are presented in Table *4*. These are maximum daily intake recommendations presented as mg intake per kg body weight. EFSA derived $BMDL_{10}$ for major PBDEs in 2011, based on $NOAEL_{10}$ in mice. EFSA recommends a MOE of 2.5 for PBDEs *i.e.* intake estimations greater than 2.5 times the EFSA derived $BMDL_{10}$ are not expected to cause a risk to human health.

1.5 Additional Persistent Organic Pollutants (POPs) discussed in this thesis

1.5.1 PCDD/Fs and PCBs

Chlorinated dioxins and furans (PCDD/Fs) are a group of tricyclic chemicals (n=210) with similar structures and chemical properties. They are accidental by-products of industrial activities such as chemical processing and incineration, having no known commercial use yet being almost ubiquitous. Polychlorinated biphenyls (PCBs) have 209 potential structures based around two benzene rings joined by a carbon to carbon bond. They were produced intentionally and widely for uses including insulators for transformers and capacitors, coolant fluids, paint and ceiling materials which benefited from their heat resistance and non-flammability. PCDD/Fs and PCBs are rarely found in the absence of one another and so are commonly studied as an additive mixture. They are recognised persistent environmental contaminants having been withdrawn from use since the 1970s. PCDD/Fs and PCBs accumulate in the food chain, concentrating in the fatty tissue of animals. Diet is the major route of human exposure to PCDD/Fs and PCBs for most individuals without specific occupational exposure. PCDD/Fs and dioxin-like compounds bind to the Ah receptor and are widely understood to cause damage to the immune system, to affect the endocrine system, to give rise to reproductive and developmental problems, and may cause cancer (EFSA 2012). PCBs and PCDD/Fs were among the initial ‘dirty dozen’ of POPs included in the first ratification of the Stockholm Convention in 2004.

1.5.2 PBDD/Fs and PBBs

Brominated dioxins and furans (PBDD/Fs) have similar physicochemical and toxicological properties to PCDD/Fs their chlorinated analogues (Van den Berg et al. 2013). They originate from similar anthropogenic sources, such as incineration, particularly of bromine-containing waste, or chemical manufacture. Polybrominated biphenyl (PBB) flame retardants are similar to PCBs in structure, manufacture, contamination pathways and toxicological impact on human health, and have some similarities in their use. Production in the USA ceased following the Michigan Firemaster incident of 1973 where PBB was accidentally introduced into animal feed. The use of PBBs as textile flame retardants was phased out from the 1970s onwards and they have not been used or manufactured in the EU since 1996 (D’Silva et al. 2004).

1.6 Thesis objectives and hypotheses

The motivation for this research was to fill important gaps in understanding the relationship between human PBDE exposure and PBDE sources in indoor environments and diets, in combination with a human health risk assessment for the PBDE concentrations determined.

Objectives of the study were to:

- Investigate human PBDE body burdens for a UK cohort and compare with previous UK and international measurements
- Determine whether the elevated BDE-209 concentrations measured in UK dusts had resulted in raised UK body burdens
- Investigate associations between paired serum and breast milk concentrations
- Measure matched indoor dust and 24 hour duplicate diet PBDE concentrations for the same cohort
- Estimate proportional exposure to indoor dusts using activity diaries.
- Investigate relationships between room contents and usage with (i) dust PBDE concentrations and (ii) PBDE body burdens using room contents and use surveys and activity diaries.

The hypotheses were:

1. Serum concentrations of PBDE have not reduced since they were restricted from use in the EU.

    To test this hypothesis serum concentrations for the study cohort we measured and compared these with serum samples collected in 2002 (Thomas, 2006) prior to use restrictions. Results are presented in Section 2.3.

2. High concentrations of BDE-209 in indoor dust in the UK have led to higher BDE-209 body burdens.

    To test this, body burdens of BDE-209 for the cohort were compared with international BDE-209 body burden data. Results are presented in Section 2.3.

Associations between BDE209 intake estimations and body burden were also investigated, with results presented in Section 5.

3. UK intakes of PBDE are not a concern to health

To test this, individual participant's estimated average and high intakes of individual PBDE congeners were compared with international health criteria values. Intakes for infants aged 1-4 were also estimated. Findings are presented in Section 2.5.

4. PBDE concentrations in breast milk can be used to predict serum concentration

To test this, PBDE concentrations in serum and breast milk for the cohort were compared and previous studies findings reviewed. Results are presented in Section 2.5.

5. Diet type is an important indicator of PBDE body burden

To test this hypothesis, results from food diaries and food frequency questionnaires were compared with body burden data. Findings are presented in Section 2.5.

6. National estimations of PBDE intake calculated from information on PBDE concentrations in common foodstuffs and national consumption survey data are suitable to estimate individual's dietary PBDE intakes.

To test this, intake determined using 24-hour duplicate diet samples for individual study participants were compared with national estimates from the UK Food Standards Agency. Findings are presented in Section 2.4.

7. Indoor exposures to PBDEs are an important contributor to overall PBDE exposure.

To do this, PBDE intake from dust and diet for the cohort were estimated and compared. Results are provided in Section 2.5.

8. PBDE levels in dust can be predicted from information about the vehicle or rooms' contents and usage.

To test this hypothesis, surveys of room and vehicle contents were carried out and associations between PBDE concentrations in the room and vehicle dust and the survey information were investigated. Results are provided in Section 2.5.

Chapter 2 Published Papers

2.1 Overview This chapter contains the four original research articles that form the basis of the thesis.

The first paper (Section Chapter 2) is a systematic review of previous studies investigating an association between matched human PBDE body burden and indoor dust and/or dietary exposure data. The remaining three papers report on different aspects of a study of matched PBDE body burden and exposures for a northeast UK cohort of 20 adults (10 cohabiting couples). Appendix C contains documents prepared for the study participants, sampling week flow chart, exposure and food frequency questionnaire, food and activity diary and room survey sheets.

I made a major contribution to each paper from study design through ethical approval, recruitment, sample collection, sample analysis, data analysis and writing of the manuscript. This contribution has been approved by co-authors in the included co-authorship forms.

Introducing each article is an overview of what was known before the work, and what it contributed to the existing evidence. The papers are presented with the systematic review first rather than in chronological order. The paper with serum and breast milk PBDE concentrations was published first as the team were keen for this UK data to be made available as soon as possible. This systematic review would have been considerably limited at the time of the initial literature review as over half of the papers included in the systematic review were published up to three years later, after completion of our field work and laboratory analysis stages.

Additional conference abstracts and poster presentations are included in Appendix D without discussion. These are examples of research undertaken concurrently to this PhD study and demonstrate development in my understanding of environmental contaminants and exposures beyond the thesis topic. Supplementary Information for the submitted papers is presented in Appendices E, F, G and H.

2.2 Associations between human exposure to polybrominated diphenyl ether flame retardants via diet and indoor dust, and internal dose: A systematic review.

Title: Associations between human exposure to polybrominated diphenyl ether flame retardants via diet and indoor dust, and internal dose: A systematic review.

Authors: Bramwell L, Glinianaia SV, Rankin J, Rose M, Fernandes A, Harrad S, Pless-Mulloli T.

Journal: Environment International

Date of publication: April 2016

2.2.1 Overview

This systematic review reported on 17 studies exploring correlations between measurements of PBDEs in human serum or milk with matched indoor dust and/or diet measurements. The review followed standard systematic review guidance from the Centre for Reviews and Dissemination (CRD, 2009) and preferred reporting items for systematic reviews (Moher *et al.*, 2009)

2.2.2 What was known before

- Concentrations of a wide range of PBDEs had been reported in human breast milks, serums, foodstuffs and indoor dusts from around the world.

- PBDE congeners from Penta-BDE commercial formulations i.e. BDEs-47, 99, 100 and 153 were found in the greatest proportions in serum, breast milk and food samples, whereas BDE-209 was found in the greatest proportions in dust in the EU and UK.

- Several independent studies had reported PBDE body burden measurements (serum or breast milk) having significant associations with matched measurements of indoor dusts as well as dietary intake information.

- Individual countries (and states in the USA) have their own fire safety regulations resulting in different use patterns of PBDEs. Greater amounts of Penta- BDE had been used in the USA leading to higher concentrations of PBDE in indoor dusts and a magnitude higher human PBDE body burdens.

- The different chemical properties of individual PBDE congeners effect their bioaccessibiliy and estimated human half-lives, thus having a fundamental impact on body burden patterns.

2.2.3 **What this study added**

- The review concluded that the dust or diet could be the major PBDE exposure source for an individual, dependant on a number of factors:

    - The country of an individual's (long term) residence, that country's fire retardant regulations, and the time of the study relative to PBDE congener use restrictions. The review confirmed the distinct congener patterns created by particularly stringent regional regulatory requirements – such as use of Penta-BDE in the USA causing mean USA BDE-47 serum measurements (~ 15 ng g^{-1} lw) to be a magnitude higher than those in the EU (~1.5 ng g^{-1} lw).

    - Duration since a country's ban of a particular PBDE congener and the congener's human half-life strongly influenced body burden patterns. Penta-mix BDEs in indoor dust and body burden were more strongly correlated in American studies and older EU studies.

    - BDE-47 was the major serum PBDE component in countries where Penta-BDE had been phased out more recently (USA, Australia) and

older studies. BDE-153 was the major serum PBDE component in countries where Penta- and Octa- BDE use had been restricted for the longest time (Denmark, Germany and Belgium). This is consistent with BDE-153 demonstrating greater persistence in human tissues.

    - Individual's proximity and interaction with items containing PBDE influence their body burdens. Dusts in bedrooms then living rooms had the strongest correlations with body burdens. Although exposure in vehicles is likely to be higher, the participants in these studies did not spend so much time in them.

- The PBDE pattern in a dust may have some degree of correlation with the pattern in serum or breast milk of an individual repeatedly exposed to the dust, given the PBDEs will originate from discreet sources with distinct congener patterns.

- PBDE sources in diet are more diffuse making correlation less likely. Strong congener correlations between diet and body burden only occur where a specific contaminated food item is a regular/major part of the diet e.g. fish from a contaminated lake.

- Discussion of strengths and limitations of various recruitment, sample collection and preparation techniques and methods of analysis.

2.2.4 **Manuscript**

Environment International 92–93 (2016) 680–694

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Associations between human exposure to polybrominated diphenyl ether flame retardants via diet and indoor dust, and internal dose: A systematic review

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ARTICLE INFO

Article history:
Received 7 August 2015
Received in revised form 4 February 2016
Accepted 11 February 2016
Available online 9 April 2016

Keywords:
PBDE
Dust
Diet
Exposure pathways
Body burden
Matched
Review

ABSTRACT

The aim of this review was to identify and appraise the current international evidence of associations between concentrations of polybrominated diphenyl ethers (PBDEs) in humans and their indoor dusts and food. We systematically searched Medline, Embase, Web of Science and Scopus (up to Jan 2015), using a comprehensive list of keywords, for English-language studies published in peer-reviewed journals. We extracted information on study design, quality, participants, sample collection methods, adjustments for potential confounders and correlations between PBDE concentrations in internal and external matrices. Of 131 potential articles, 17 studies met the inclusion criteria and were included in the narrative synthesis. We concluded that three key factors influenced correlations between external and internal PBDE exposure; half-life of individual congeners in the human body; proximity and interaction between PBDE source and study subject; and time of study relative to phase out of PBDE technical products. Internal dose of Penta-BDE technical mix congeners generally correlated strongly with dust. The exception was BDE-153 which is known to have higher persistence in human tissues. Despite the low bioaccessibility and short half-life of BDE-209, its high loading in dusts gave strong correlations with body burden where measured. Correlations between PBDE concentrations in duplicate diet and body burden were not apparent from the included studies. Whether dust or diet is the primary exposure source for an individual is tied to the loading of PBDE in dust or food items and the amounts ingested. Simple recommendations such as more frequent hand washing may reduce PBDE body burden.

1. Introduction

Polybrominated diphenyl ethers (PBDEs) are a class of brominated flame retardant, which have been widely used to meet fire safety regulations for fabrics, furnishings, electronics and vehicles since the 1970s. PBDEs are additive flame retardants, meaning that they are mixed into plastics or foam without forming chemical bonds. Fabrics and textiles can also be treated with PBDE commercial mixtures to provide protection. During the lifetime of products, PBDEs can leach out, thus becoming ubiquitous in indoor air and dust (Harrad et al., 2010). From there they migrate further into the wider environment and bioaccumulate through food chains (Harrad and Diamond, 2006). The human body burden of PBDEs increased dramatically from the 1970s until the 1990s (Frederiksen et al., 2009b; Hites, 2004; Meironyte et al., 1999) reflecting both wide use and persistence of these lipophilic chemicals. It is likely that regulations restricting PBDE use, e.g. Directives 2002/95/EC and 2003/11/EC and EC Designation 2008/C116/4, have been instrumental in reducing human exposure (Frederiksen et al., 2009b). However, the effects of such measures are slow to impact on levels found as contaminants in human tissue. Furthermore, recovery and recycling of electronics, particularly where unregulated in developing countries, is an additional new source of exposure (Athanasiadou et al., 2008; Ionas et al., 2014; Labunska et al., 2014; Liu et al., 2008). Potential adverse human health effects of PBDE exposure and body burden are well documented and include reproductive toxicity, neurotoxicity, endocrine activity, DNA damage and immune effects (EFSA, 2011; Kim et al., 2014; Linares et al., 2015; Lyche et al., 2015; US-EPA, 2010). The bioaccessibility of ingested PBDEs has been estimated to be 32-60% for tri- to hepta-BDEs, and 14-25% for deca-BDE (Abdallah et al., 2012; Fang and Stapleton, 2014). PBDE bioaccessibility generally decreases with increasing octanol-water partitioning coefficient (Log K_{ow}) a measure of relative solubility in lipid and water (Abdallah et al., 2012; Fang and Stapleton, 2014). It is widely accepted that PBDEs can have

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http://dx.doi.org/10.1016/j.envint.2016.02.017
0160-4120/

substantial half-lives in humans. There is a general trend of shorter half-lives for the higher brominated compounds, with estimates of residence time for BDE-209 of just a few days, and for main congeners of the technical Penta-BDE mixture (i.e. BDE-47, -99, -100) around two to four years (Geyer et al., 2004; Thuresson et al., 2006). Over the last few years, a number of studies have investigated matched internal and external PBDE exposure. A thorough review of such studies may reveal common patterns, which may generate recommendations for reducing exposure and identify future research needs. This new evidence will help to determine whether external exposure measurements can be used as indicators of human internal PBDE exposure. The aims of this systematic review were: (1) to identify, appraise and summarise the current international literature on the association between PBDE concentrations measured in food items and indoor dusts with human body burdens; and (2) to determine the relative contributions made by indoor dust ingestion and dietary exposure to PBDE body burden for general non-occupational human exposure.

2. Methods

2.1. Literature search and selection criteria

The process of this review followed the guidance for conducting systematic reviews from the Centre for Reviews and Dissemination (CRD, 2009) and 'Preferred Reporting Items for Systematic Reviews' guidelines (Moher et al., 2009). Papers were identified through searches of the environmental and medical literature databases (Medline, Embase, Web of Science, Scopus) using relevant terms for PBDEs, internal dose, external exposure and matched exposure. The Boolean operators 'AND' and 'OR' were used to combine topic areas; *i.e.* ($bde OR pbde OR pbdes OR (polybrominated and ('diphenyl' de OR diphenyl) and ('ethers' de OR ethers))) AND (serum$ OR plasma$ OR blood$ or milk$ OR internal OR body burden$ OR exposure$) AND (diet$ OR food$ OR dust$ OR air$ OR indoor$ OR environment$ OR exposure$ OR factor$ OR lifestyle$ OR source$ OR behav$) AND (match$ OR pair$ OR relation$ OR association$ OR evidence$ OR predict$). A comprehensive description of the search strategy is available in SI1. Reference lists of the identified published studies were also scanned and experts in the field were consulted.

Studies were included if they met the following inclusion criteria: a) explored correlations in PBDE concentrations between paired human internal dose (serum or milk) and indoor house dust, and/or correlations between paired human internal dose (serum or milk) and diet, b) were published in the English language, c) were full original papers which were published in a peer-reviewed journal available either on-line or from the British Library. Databases were searched for papers published between 1974 to January 2015. There were no limits on the year of publication (up until Jan 2015) or the age of study participants. Studies were not included if the dust exposure measurement was purely occupational or from a hobby.

One reviewer (LB) scanned through all abstracts after the initial article selection and excluded only obvious non-eligible studies. A second reviewer scanned titles and abstracts of a 15% sample of the identified studies and confirmed decisions on inclusion. A sample of the papers that met the inclusion criteria (20%) were formally reviewed by two independent reviewers using a data extraction form modified from Glinianaia et al. (Glinianaia et al., 2004). Data extracted included information on study design, sample descriptors and collection methods, analytical and statistical methods, confounders and correlations. Concentrations of PBDE in human serum or milk (lipid weight) were used to indicate internal dose. Concentrations of PBDE in indoor dusts or in duplicate diets (per body weight) were used as the indicators of exposure. The correlations calculated for pairs of internal dose and exposures were explored.

We present a narrative synthesis of the data, as a formal meta-analysis was not possible given the heterogeneity of samples, particularly differences in: a) fire prevention regulations and technical product usage between countries (and between states in the USA); b) sample collection methods; c) congeners analysed and reported; and d) analysis and reporting of correlations between internal and external exposures.

2.2. Study quality

The quality data extraction form was based on that used by Roth and Wilks (2014) and 'Harmonization of Neurodevelopmental Environmental Epidemiology Studies' (HONEES) criteria (Youngstrom et al., 2011). Quality assessment evaluated study design (description of setting, location, data collection dates, study size), study population and sampling (eligibility criteria, recruitment methods, response rate, participant description, representation of population to whom results would be generalised), variables for adjustment (discussion of and accounting for confounders and bias), data measurement (methods of measurement, quality controls, fit with literature) and outcome measurement (statistical methods and description). Laboratory measurement quality considerations included ^{13}C internal standardisation coupled with GC-HRMS measurement, and the successful use of regular procedure blanks and reference materials. Studies were classified, regarding provision of this information, as: yes (1), no or unclear (0), or partially (0.5). Based on these criteria, three quality groups were formed: scores of 10–12 were rated high, 4–9 moderate and 0–3 low. When drawing conclusions, studies with a low quality score were given less weight. Throughout the review process we referred to recommendations from 'Strengthening the Reporting of Observational Studies in Epidemiology' (STROBE) guidelines (von Elm et al., 2007).

3. Results

A flow diagram of numbers of articles identified by the literature searches, screened, assessed for eligibility and included in the review, with reasons for exclusion at each stage is presented in Fig. 1. Database searches elicited 408 articles. A title and abstract review resulted in 131 original peer reviewed papers. The abstracts and, where necessary, full articles were reviewed in detail resulting in further exclusions. Twenty-three articles were included in the systematic review, concerning 17 studies which met our inclusion criteria and were included in the narrative synthesis (Fig. 1). For six of these studies, key information was extracted from additional papers to those containing the correlation analysis. The additional papers are referred to in Tables 1 and 2.

3.1. Participant characteristics and study methods

A summary of study designs, participant characteristics, sampling methods, adjustments for confounders and quality assessment for the 17 included studies is presented in Table 1. Seven of the studies took place in Europe — predominantly Scandinavia and Northern Europe, six studies took place in the USA, three took place in Australasia, and one in South Central Asia. The specific countries where the studies were conducted are included in Table 1. Only one study stated its design, this was a convenience cross-sectional sample, (Watkins et al., 2012) so recruitment information was used to deduce design for the other studies where possible. Samples recruited from a previous study's cohort or by word-of-mouth appeared to be on the basis of convenience (Coakley et al., 2013; Imm et al., 2009; Sahlström et al., 2015; Stasinska et al., 2014; Toms et al., 2009; Whitehead et al., 2015). Where participants were recruited because they were pregnant or were undergoing medical treatment, the design appeared to be prospective (Frederiksen et al., 2010; Wu et al., 2007). If recruitment was based on specific businesses or accommodation, the studies were considered to be retrospective (Ali et al., 2014; Roosens et al., 2009). Remaining studies were classed cross-sectional (Bjorklund et al., 2012; Cequier et al., 2015; Fromme et al., 2009; Johnson et al., 2010; Stapleton et al., 2012) or of unclear design (Karlsson et al., 2007).

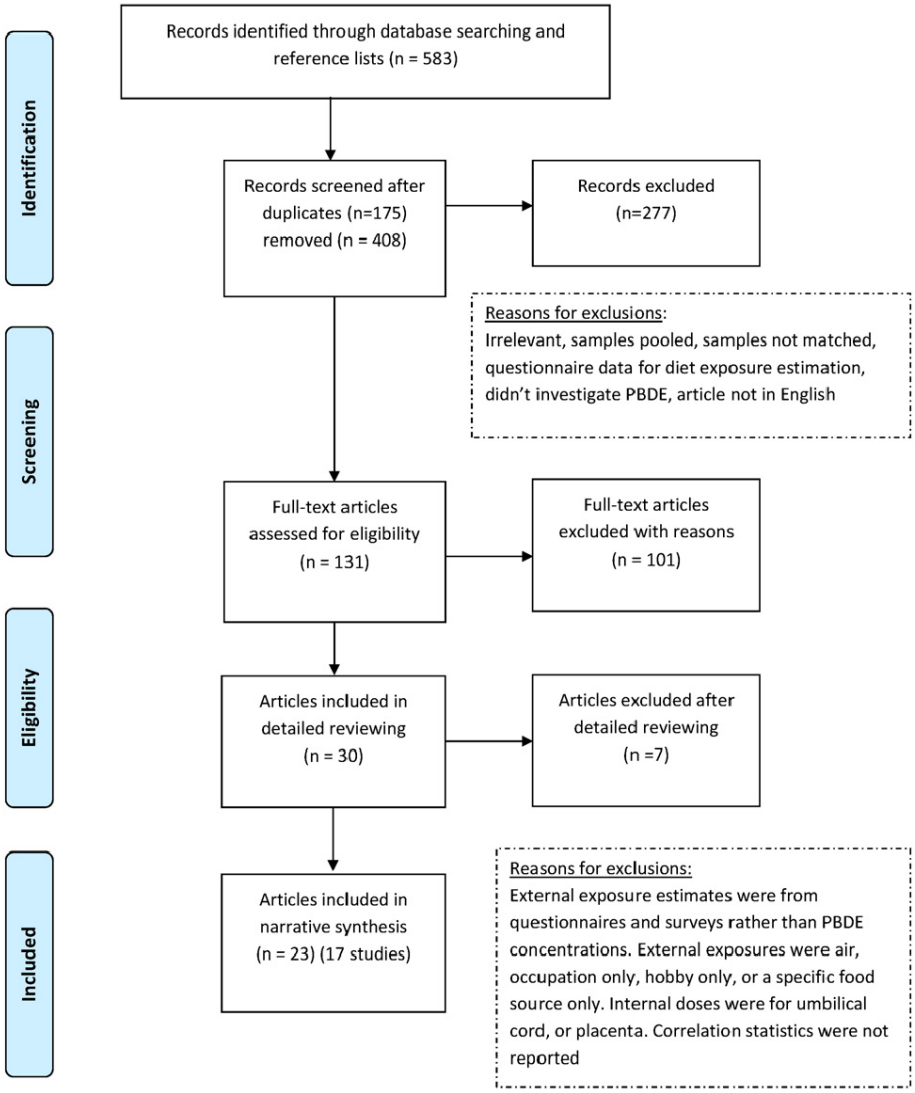

Fig. 1. PRISMA flow diagram of numbers of studies identified by the literature searches, screened, assessed for eligibility and included in the review

All studies were published from 2007 to 2015, and samples were collected between 2004 and 2012. Dates and details on participants' gender and ages, and sampling strategies for individual studies, are provided in Table 1. Thirteen studies used blood as the internal dose measure and four used breastmilk. All studies measured indoor dust, twelve collected information on dietary habits and two measured duplicate diet samples. Nine of the studies exclusively sampled women. The majority of studies involved women of reproductive age. Mixed male and female studies generally had wider age ranges, except for one study where subjects were students aged 20–25 years (Roosens et al., 2009) and another of toddlers aged 12–36 months (Stapleton et al., 2012). Where human milk was used as the measure of internal dose, participants were usually primiparous breastfeeding women (Bjorklund et al., 2012; Coakley et al., 2013; Wu et al., 2007) but not exclusively (Toms et al., 2009). Where reported, milk samples included studies that ranged in duration from: (i) 14–21 days (Bjorklund et al., 2012); (ii) 2–8 weeks (Wu et al., 2007); and (iii) 2–11 months postpartum (Toms et al., 2009).

There are no standard procedures for dust collection. The simplest dust sampling method used was to take a sample from a vacuum cleaner dust bag (VCBD) from the home which was used for seven of the studies. Where dusts were collected directly by the researcher, different areas and surfaces were sampled, sometimes including vehicles and workplaces and different rooms separately (Ali et al., 2014; Watkins et al., 2012). These aimed to maximise the likelihood of detecting differentials. Rooms were generally selected on the basis that it was the room(s) that the participant spent most time in, for example, the child or student's room (Roosens et al., 2009; Stapleton et al., 2012), the main living area (Cequier et al., 2015), the most commonly used rooms (Wu et al., 2007) or the living room and bedroom combined (Karlsson et al., 2007).

The two studies that included both dust and diet measurements estimated the proportion of internal dose attributable to each. Roosens et al. (2009) compared PBDE exposure from food intake and dust ingestion using average and high dust ingestion rates from Jones-Otazo et al. (2005). Fromme et al. (2009) used Lorber's simple one-compartment toxicokinetic model (Lorber, 2008) with ingestion, inhalation, absorption bioavailability and half-life estimations. Studies investigating the strength of different sources as predictors of body burden used multivariate regression models (Stapleton et al., 2012; Watkins et al., 2012).

3.2. Study findings

3.2.1. Major congeners reported in each matrix

Table 2 provides a summary of major congener concentrations for each measured sample matrix reported. Figs. 2 and 3 provide an

Table 1
Summary of study designs, participant characteristics, sampling methods, adjustments for confounders and quality assessment (presented in alphabetical order)

Study reference(s)	Country, data collection period, sample number, gender and age	Study design, paired sample size and recruitment details	Matrices measured for dose and exposure assessment, timing of collection	Additional information collected	Adjustments made for confounders	Quality score
1. Ali et al. (2014)	Pakistan 2011 n = 61 M & F 17–55 years	Recruited from clothing stores (n = 15), university rooms/office (n = 16) and electronics stores (n = 30)	*Blood* (fasted), 7–8 ml collected, serum analysed, *Dust* swept from 4–8 m^2 of floor of store or university hostel rooms/office, sieved <500 μm Both samples collected within one month	Age, gender, occupational history, details of electronics, foam chairs and date of last cleaning	None	Moderate
2. Bjorklund et al. (2012)	Sweden 2008 n = 18 F –	Primiparous, Swedish born, random selection from a hospital birth registry, even distribution throughout year	*Milk* collected 14–21 days postpartum, 35 g extracted for analysis *Dust* (house) VCBD and RCD (from main living area) sieved <500 μm, 10–174 mg extracted Both samples collected within one week	Age, height, weight before pregnancy, birth weight of the child, weight change during and after pregnancy, education, smoking and dietary habits	None	High
3. Cequier et al. (2014a, 2015)[a]	Norway 2012 n = 46 F –	Mother child cohort recruited through two primary schools	*Blood* 10 ml collected, serum analysed *Dust* (house) from entire living room floor Timing not reported	Dietary habits, demographic information and household factors	None	Moderate
4. Coakley et al. (2013)	New Zealand 2007–2010 n = 33 F 20–31 years	Primiparous mothers that had provided milk for 4th WHO POPS in milk survey	*Milk* average 250 ml collected, 2nd and 3rd months postpartum *Dust* (house) from 1–4 m^2 of floor in living room sitting area, vacuumed for 2–4 min *Dust* (mattress) n = 16 Timing not reported	Demographics and household contents	None	Moderate
5. Frederiksen et al. (2009a, 2010)[a], Vorkamp et al. (2011)	Denmark 2007 n = 51 F –	Underwent scheduled caesarean section	*Blood* collected during procedure, plasma analysed *Dust (house)* VCBD collected before and after delivery, sieved <75 μm + maternal plasma (and umbilical cord plasma). Air and VCBD pre and post delivery	Lifestyle and dietary habits information, umbilical cord plasma and pooled milk samples also analysed	None	Moderate
6. Fromme et al. (2007, 2009)[a]	Germany 2005 n = 61 M&F 15–56 years	34 households, 27 F (age 14–60 years) and 23 M (age 15–56 years) with no occupational exposure, part of INES study	*Blood* 30 g collected, serum analysed *Duplicate diet* 7 days, 30 g extracted for analysis *Dust* (house) VCBD, sieved <2 mm, 1 g extracted and analysed Serum samples collected during the diet collection week	Sociodemographic characteristics, living conditions, building characteristics, possible sources of contaminants, dietary habits[a]	None	Moderate
7. Imm et al. (2009)[a]	USA 2008 n = 44 M & F 43–77 years	38 households from existing cohort of Great Lakes frequent and infrequent consumers of sport fish	*Blood* 15–20 ml collected *Dust* (house) VCBD, sieved <1 mm Dusts collected prior to blood sample collection	XRF measurements of BR content of individual items in the home, demographics, dietary habits, hobbies with plastics, foam or fabrics, work environments	None	Moderate
8. Johnson et al. (2010)	USA 2007–8 n = 24 M & F –	12 couples seeking fertility treatment	*Blood* 5 ml collected, serum analysed *Dust* (house) VCBD, sieved <150 μm, Both samples collected on same day	Demographics, dietary habits, home age, heating type, system used; hours of TV and computer use; primary vehicle and hours of use; boat use; hobbies using plastic, foam, or fabric; and work environment	None	Moderate
9. Karlsson et al. (2007)[a]	Sweden – n = 5 – –	Non-occupationally exposed sample living in same home ≥5 years	*Blood* 10 ml collected, plasma analysed *Dust (house)* living room and bedroom floors and furniture, 1–2 g collected Samples taken on same day	Number of electronic devices, living area size, floor material	None	Low
10. Roosens et al. (2009)	Belgium 2007 n = 19 M & F 20–25 years	Residents of Belgium since childhood; living at the same college for 3 years	*Blood* 10 ml collected plasma analysed *Duplicate diet* 7 days *Dust* from students room floor, 4 m^2 or bare floor vacuumed for 4 min, sieved <500 μm, Dust and bloods collected on last day of duplicate diet	Home location, furnishings, electronics/electric appliances and lifestyle such as smoking and transportation	None	Moderate
11. Sahlstrom et al. (2014, 2015)	Sweden 2009–10 n = 20 F	First time mothers with toddlers aged 11 months already participating in POPUP study	*Blood* collected, 0.5–5 g serum analysed *Dust* (house) 1 m above the floor in the living room, kitchen, bedroom and/or hall-way	Dietary habits	None	Moderate

(continued on next page)

Table 1 (*continued*)

Study reference(s)	Country, data collection period, sample number, gender and age	Study design, paired sample size and recruitment details	Matrices measured for dose and exposure assessment, timing of collection	Additional information collected	Adjustments made for confounders	Quality score
12. Stapleton et al. (2012)	24–40 years USA 2009–10 n = 77 M & F 12–36 months	Children with no prior diagnosis of thyroid problems recruited via paediatric clinic patient lists	Samples taken on same day *Blood* 4 ml collected, serum analysed *Dust* (house) entire floor-surface of room in which child spent most active time, sieved <500 μm, collected during the same visit (except nine bloods collected at clinic) *Handwipes* also collected during same visit	Short questionnaire about the child and parents' education levels, child's length of time breastfed, ethnicity and time away from home	Children's sex, age race, parents' education levels, duration of breast-feeding, time children spent away from home, dust concentrations, and handwipe levels	High
13. Stasinska et al. (2013, 2014)	Australia 2009–11 n = 29 F ≥18 years	Pregnant women (38 weeks gestation) from the AMETS *cross-sectional* study	*Blood* 6 ml collected, plasma analysed *Dust* (house) VCBD 20 g, home, sieved <600 μm, Participants brought dust sample when attending clinic for blood sample collection	Demographics, anthropogenics, occupational history, medical history, smoking, home type and age, number and age of electronics, dietary habits, pregnancy, weight gain and infant anthropometrics	None	Moderate
14. Toms et al. (2009)[a]	Australia 2007–8 n = 10 F 27–40 years	Breast-feeding mothers (2–11 months postpartum) by word-of-mouth	*Milk* 100 ml collected between 2–11 months postpartum *Dust* (house) floor dust from one floor of house, sieved <2 mm Most pairs sampled within 1 month	Dietary habits, demographics, house characteristics, daily time spent on computer and in car	None	Moderate
15. Watkins et al. (2012)	USA 2009 n = 31 M&F –	*Convenience & cross-sectional* sample of non-smoking, adult workers, in good health, spending ≥20 h/week in an office	*Blood* 10 ml collected, serum analysed *Dusts* (house & office) entire floor and surface area of main living area, bedroom and office vacuumed 10 min, sieved <500 μm *Handwipes* at work ≥60 min since last hand wash, all matrices collected in same week, serums at end of work week	Dietary habits, personal habits, average hours at work, vehicle use, handwashing, dust from vehicles also analysed	None	High
16. Whitehead et al. (2013, 2015)	USA 2006–7 n = 48 F –	Mothers of children aged 0–7 years in CCLS study	*Blood*, serum analysed *Dusts* (house) VCBD, sieved <150 μm Up to five months between paired sample collections	Demographics, anthropometrics, dietary habits (modified Block FFQ) geographical, residential, sources of PBDE in the home	Hispanic ethnicity, country of origin, household annual income	High
17. Wu et al. (2007)	USA 2004–5 n = 11 F ≥18 years	First time mothers via an obstetrics office and maternity centre, living in same home ≥3 years	*Milk* 50 ml collected between 2–8 weeks postpartum *Dusts* (house) researcher collected, surface area recorded, sieved <125 μm as soon after milk as was convenient for participants (1–43 days)	Health, residential history, electronic products, foam furniture, pre-pregnancy diet, occupational history, hobbies, home renovation, and transportation	Multiple regression used to adjust for potential confounding by dietary (meat, fish and dairy) or personal factors	High

For left censored data (values below LOD/LOQ/MLD) in statistical analysis studies 3, 4, 6, 8, 15 and 13 used LOQ * 0.5, studies 2, 11 and 16 used LOQ/√2, studies 1 and 10 used LOQ * fraction above LOD and studies 5 and 7 used only values above LOQ.
For correlation, studies 1, 3, 5, 6, 7 and 8 used Spearman's rank correlation for non-parametric data and studies 2, 4, 13, 15, 16 and 17 reported log or ln transformed data to enable use of Pearson's correlation for normally distributed datasets.
For quality control, studies 1, 2, 3, 4, 11, 13 and 17 reported using NIST SRM 2585 for indoor dust, study 10 used NIST SRM2584 for house dust, study 16 used NIST SRM for serum, studies 5, 11 and 12 took part in AMAP Ring inter-laboratory tests for POPs in serum, study 17 took part in QUASIMEME inter-laboratory testing. Studies 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 15 and 16 reported subtracting method blanks. Studies 1, 2, 4, 5, 6, 9, 10, 11, 12, 14, 16 and 17 reported using ^{13}C labelled standard for BDE-209.
M: male.
F: female.
SRM: standard reference material.
NIST: National Institute of Standards and Technology — US Department of Commerce.
RSD: relative standard deviation.
POPUP: Persistent Organic Pollutants in Uppsala Primiparous.
AMETS: Australian Maternal Exposure to Toxic Substances.
CCLS: California Childhood Leukaemia Study.
Block food frequency: (Block et al., 1990).
AMAP: Artic Monitoring and Testing Programme.
QUASIMEME: Community of Practice for Marine Environmental Measurements.
VCBD: Vacuum Cleaner Bag Dust.
RCD: Researcher Collected Dust.
Additional article references for Tables 1 & 2: Cequier et al. (2014a); Frederiksen et al. (2009a); Fromme et al. (2007); Mannetje et al. (2010); Sahlstrom et al. (2014); Stasinska et al. (2013); Whitehead et al. (2013).
[a] Home air PBDE concentration was also sampled in six marked studies, but this is beyond the scope of this review and therefore not presented here.

indication of relative differences between matrices and geographical regions. The four studies using human milk as a measure of internal dose reported BDE-47 and BDE-153 to be the predominant PBDE congeners. Their total concentrations and proportions varied between EU, Australasia and USA regions as might be expected based on varied national usage of PBDE flame retardants. Two studies noted a proportion of participants having higher BDE-153 than BDE-47 in milk; 20% in Australia (Toms et al., 2009) and 3% in the USA (Wu et al., 2007). BDE-209 was analysed in three of the studies, with detection rates of 24% in the USA (Wu et al., 2007), 60% in Australia (Toms et al., 2009) and 97% in New Zealand (Coakley et al., 2013). Variation in methods and improvements in limits of detection for BDE-209 for these studies (0.1–1.0, 0.3 and 0.065 ng/g respectively) can be expected to have influenced detection rates.

BDE-47 was the major congener in blood (making up 45-100% of the total serum PBDE) in earlier studies (Karlsson et al., 2007) and in the USA and Australia where penta-BDE technical mix (e.g. DE-71) was more heavily used and phased out more recently (Imm et al., 2009; Johnson et al., 2010; Stapleton et al., 2012; Stasinska et al., 2014). BDE-153 was the major congener in blood in Denmark, Germany and Belgium (Frederiksen et al., 2010; Fromme et al., 2009; Roosens et al., 2009) where penta- BDE use was lower than that in the USA and penta- and octa-BDE were banned in 2004. These findings indicate that regional PBDE regulations and use patterns, time of study relative to phase out of PBDE use and half-life of PBDE congeners are key factors in predicting internal dose of different congeners.

BDE-209 was the predominant congener in dust for almost all studies. The next most abundant congeners in dust tended to be BDEs-99, followed by -47 (Coakley et al., 2013; Fromme et al., 2009; Johnson et al., 2010; Karlsson et al., 2007; Stasinska et al., 2014). Differences in congener patterns were again noticeable between the USA and Europe, indicating the importance of regional use patterns in predicting exposure to PBDEs from dust. European studies demonstrated the highest congener percentages of BDE-209 in dust, with averages reported around 70–90% (Bjorklund et al., 2012; Fromme et al., 2009; Karlsson et al., 2007; Roosens et al., 2009). USA studies had lower BDE-209 proportions (0–60%) (Johnson et al., 2010; Wu et al., 2007) and Australia and New Zealand dust loadings appeared to be somewhere between the USA and EU, with BDE-209 making up approximately 66% of the PBDE total (Stasinska et al., 2014).

A small percentage of dust samples had greater ∑ penta-BDE concentrations in dust than BDE-209 concentrations (Frederiksen et al., 2010; Johnson et al., 2010; Wu et al., 2007) indicating a particular source within that indoor environment. Bjorklund et al. (2012) found concentrations of individual congeners were higher in samples collected from ≥1 m above flooring vs VCBD (median 2–3 times), however it is unclear whether this trend would be observed in other studies.

The major contributing PBDE congeners in the Belgian duplicate diet study were BDE-47 > -99 > -153 (Roosens et al., 2009). Major congeners in the German duplicate diets were different with a predominance of BDEs-99, -183 then -47 (Fromme et al., 2009).

3.3. Intermatrix correlations

A summary of the correlations between paired internal and external exposure measurements reported in the 17 included studies is provided in Table 2. BDE-47 in dust and internal dose measurements were significantly correlated ($p < 0.05$) in seven of the studies (including three of the four studies using milk), BDE-99 in four studies, BDE-153 in three studies and BDE-209 in only one (Coakley et al., 2013).

The strongest correlation reported was for technical Penta-BDE mix components BDE-47,-99, and -100 ($\sum BDE_3$) between handwipes and serum in children aged 12–36 months (Stapleton et al., 2012). This finding indicates proximity between source and receptor to be a key factor in predicting strength of correlation between internal dose and exposure measurement. Also very strongly correlated were paired BDE-47 in VCBD dust and blood, particularly in American studies and older EU studies (Frederiksen et al., 2010; Johnson et al., 2010; Whitehead et al., 2015), indicating the importance of time of study relative to PBDE use phase out. Similarly strongly correlated were BDE-99 in VCBD dust and blood (Johnson et al., 2010; Whitehead et al., 2015), BDE-47 in house dust and milk (Wu et al., 2007), ∑ penta-BDEs in bedroom dust and blood (Ali et al., 2014; Watkins et al., 2012) and BDE-153 in mattress dust and serum (Coakley et al., 2013). Significant correlations between BDE-153 in dust and internal dose were also found for university hostel dust (Ali et al., 2014). These findings indicated that time spent in proximity to the PBDE source is a key factor for predicting associated internal dose. Associations between BDE-153 in children's handwipes and serum were weaker than their associations for $\sum BDE_3$ (∑ BDE-47, -99, -100) (Stapleton et al., 2012), an indicator of the importance of congener half-life when predicting internal dose. BDE-153 has the longest PBDE residency time in humans, estimated to be 14-16 years (Geyer et al., 2004), leading to body burden proportions increasing over time in relation to other congeners. Where BDE-209 analysis in blood was successful, concentrations were reported to be 50% of the total PBDE body burden, indicating strong on-going exposure given its relatively short biological half-life.

Where congeners associated with particular technical mixtures were significantly correlated with each other in dust the findings were reported to indicate one or more items containing such technical mix in the area sampled (Bjorklund et al., 2012; Frederiksen et al., 2010). Coakley et al. (2013) reported strong and significant correlations between congeners from the same technical product, for Penta-BDE, Octa-BDE and Deca-BDE technical mixes, both within and between matrices, again suggesting a specific source or sources of the technical product. BDE-209 was not found to correlate with congeners in other technical mixtures indicating different sources or applications. This indication would also fit with data sets where a small percentage of dust samples had greater ∑ penta-BDE concentrations in dust than BDE-209 concentrations (Frederiksen et al., 2010; Johnson et al., 2010; Wu et al., 2007).

Thirteen studies investigated house characteristics and contents as predictors of dust or serum PBDE concentrations. Two studies reported urban home dusts had significantly higher penta-BDE than rural home dusts (Cequier et al., 2015; Coakley et al., 2013). Other home characteristics predicted dust PBDE for only one study each e.g. age of home and whether home was detached (Cequier et al., 2015), older carpet underlay (Coakley et al., 2013), number of flat screen TVs, number of TV/gaming consoles, number of DVD/video players, and number of electronics (Cequier et al., 2015). Subjects with crumbling or exposed foam in their homes were found to have higher serum levels of BDE-47 and -99 than those who did not (Whitehead et al., 2015). Imm et al. (2009) used a portable X-ray fluorescence (XRF) spectrometer to measure the bromine content in household and vehicle items and reported that Br concentrations in pillows ($r = 0.69$, $p = 0.005$) and vehicle seat cushions ($r = 0.56$, $p = 0.03$) correlated significantly with serum concentrations. When the importance of different rooms was considered, dusts from bedrooms and main living areas indicated the strongest correlations with body burden over office workplaces (Ali et al., 2014; Watkins et al., 2012). This finding highlighted the importance of time spent in locations with sources when estimating exposure. Two studies from the USA estimated the proportional impact of variants on body burden. The study of toddlers reported that handwipe levels, child's sex, child's age, and father's education accounted for 39% of the variation in serum ∑ BDE-47,-99,-100 ($\sum$ penta-BDE_3) levels, yet 39% of the variation in serum BDE 153 came from age, handwipe levels, and breastfeeding duration (Stapleton et al., 2012). Watkins et al. (2012) reported that main living area dust and handwipes predicted 55% of the variation in serum.

The studies in Germany and Belgium measuring both duplicate diet and dusts as predictors of serum PBDEs both reported dietary exposure to be the greater. Fromme et al. (2007) reported the dietary

Table 2
Total concentrations of major PBDE congeners in milk, blood, dust and duplicate diet samples and correlations between them (presented in alphabetical order).

Study, measure of external exposure	Total number of PBDE congeners analysed	BDE congener	Milk ng/g lw	Blood ng/g lw	Dust ng/g dw	Diet ng/g ww	Correlations	
			Median (range) % detect				r	p
1. Ali et al. (2014)	Serum — 8	BDE-47	–	0.9 (<0.5–4)	3 (<0.2–365)	—	−0.85	0.32
electronic store dust	Dust — 11	BDE-99	–	0.7 (<0.4–2.8)	3 (<0.2- 345)	—	**0.54**	**<0.01**
		BDE-153	–	0.8 (<0.2–3.7)	1.2 (<0.2–150)	—	0.01	0.48
		∑pentaPBDE	–	2.5 (0-11)	10 (1-1150)	—	0.15	0.21
		BDE-209	–	–	155 (<2–51,500)	—	—	—
Clothing store dust		BDE-47	–	0.8 (<0.5–3)	1.7 (<0.2–6.5)	—	0.07	0.4
		BDE-99	–	0.5 (<0.4–1)	2.0 (<0.2–8.8)	—	−0.16	0.28
		BDE-153	–	0.8 (0.2–2)	0.6 (<0.2–1.5)	—	0.26	0.18
		∑pentaPBDE	–	2.5 (0.5-5)	5 (0.8-19)	—	0.19	0.25
		BDE-209	–	–	45 (<2–195)	—	—	—
University hostel dust		BDE-47	–	1.0 (<0.5–11)	2.2 (1–12.5)	—	**0.56**	**0.01**
		BDE-99	–	0.8 (<0.4–11)	3.5 (1–23)	—	**0.48**	**0.03**
		BDE-153	–	1.1 (0.4–2.2)	1 (0.5–5)	—	**0.43**	**0.04**
		∑pentaPBDE	–	3 (1-25)	7.5 (2.5-50)	—	**0.64**	**<0.01**
		BDE-209	–	–	65 (12–205)	—	—	—
2. Bjorklund et al. (2012)	Milk — 10	BDE-47	0.85 (0.41–12) 72	–	15 (1.5–47) 100	—	**0.51**	**0.029**
VCBD	Dust — 16	BDE-99	– (<0.16–1.4) 17	–	13 (0.074–68) 100	—	—	—
		BDE-153	0.58 (0.26–1.6) 100	–	2.2 (0.12[c]–12) 95	—	0.037	0.88
		BDE-209	–	–	280 (110–6600) 100	—	—	—
≥1 m above floor		BDE-47	–	–	38 (8.5–250) 100	—	0.281	0.109
		BDE-99	–	–	25 (2.3[c]–130) 94	—	—	—
		BDE-153	–	–	6.0 (0.96–14) 100	—	0.322	0.208
		BDE-209	–	–	520 (190–9300) 100	—	—	—
3. Cequier et al. (2014a, 2015)	Serum — 7	BDE-47	–	0.49 (<LOD–11) 74	126 (>LOD–1510) 100	—	−0.23	ns
	Dust — 9	BDE-99	–	0.13 (<LOD–2.6) 17	171 (<LOD–2,610) 98	—	—	—
		BDE-153	–	0.82 (>LOD–5.1) 100	26.0(<LOD–254) 98	—	−0.18	ns
		BDE-209	–	–	325 (<LOD–204,000) 98	—	—	—
		∑$_7$PBDE	–	2.3 (NA-23)	426 (NA-5,125)[e]	—	**−0.33**	**<0.05**
4. Coakley et al. (2013)	Milk and dust — 16	BDE-47	2.140 (0.317–7.710) 100	–	24.2 (0.3–98) 97	—	**0.39**	**<0.05**
floor dust		BDE-99	0.560 (0.0662–1.290) 100	–	31.5 (3.3–219.1) 100	—	0.33	ns
		BDE-153	0.517 (0.142–3.820) 100	–	4.6 (0.3–58.9) 88	—	0.15	ns
		BDE-209	0.1905 (0.0653–3.140) 97	–	598 (28.8–27,394) 100	—	**0.37**	**<0.05**
Mattress dust		BDE-47	2.140 (0.317–7.710) 100	–	46.3 (6.5–288.4) 100	—	**0.52**	**<0.05**
		BDE-99	0.560 (0.0662–1.290) 100	–	41.8 (8.1–540.3) 100	—	0.41	ns
		BDE-153	0.517 (0.142–3.820) 100	–	6.7 (0.3–58.2) 94	—	**0.74**	**<0.005**
		BDE-209	0.1905 (0.0653–3.140) 97	–	1018 (106—21,956) 100	—	**0.5**	**<0.05**
5. Frederiksen et al. (2009a, 2010), Vorkamp et al. (2011)	Serum and dust — 11	BDE-47	–	0.38 (<0.011–7.88) 80	16.9 (3.29—962) 100	—	**0.52**	**0.0006**
VCBD before delivery		BDE-99	–	0.11 (<0.053–18.5) 37	13.6 (2.72—1,764) 100	—	0.36	0.1372
		BDE-153	–	1.13 (<0.013–36.0) 98	2.48 (0.547—182) 100	—	0.11	0.462
		BDE-209	–	1.71	332	—	0.49	0.062

Table 2 (*continued*)

Study, measure of external exposure	Total number of PBDE congeners analysed	BDE congener	Milk ng/g lw	Blood ng/g lw	Dust ng/g dw	Diet ng/g ww	Correlations	
			Median (range) % detect				r	p
				(<0.66–3.85) 94	(55.7 – 58,064) 100			
After delivery		BDE-209	–	–	432 (54.5 – 79,783) 100	–	–	–
6. Fromme et al. (2009)	Serum and diet – 17 Dust – 16	BDE-47	–	1.81 (0.23–6.44) 87	9.08 (1.71 – 255)	0.15 (0.06–1.37)[a]	–	ns
		BDE-99	–	0.75 (0.19–2.19) 77	12.5 (1.83 – 390)	0.18[F], 0.25[M] (0.06–2.17)[a]	–	ns
		BDE-153	–	2.37 (0.86–8.19) 94	2.69 (0.30 – 41.1)	0.05 (0.02–0.18)[a]	–	ns
		BDE-209	–	–	312 (29.7 – 1,460)	–	–	ns
7. Imm et al. (2009)	Serum – 24 Dust – 8	BDE-47	–	19.11*(–)100	520* (–)100	–	–	ns
		BDE-99	–	4.06*(–) 55	614* (–)97	–	–	ns
		BDE-153	–	4.53*(–) 11	73* (–) 84	–	–	ns
		BDE-209	–	<0.5*(–) 0	1389* (–) 100	–	–	ns
8. Johnson et al. (2010)	Serum – 11 Dust – 31	BDE-47	–	17 (<LOD-83)	390 (100–8627)	–	**M, 0.81**	**0.002**
			–	100	100	–	**F, 0.80**	**0.002**
		BDE-99	–	2.4 (<LOD-12)	427	–	**M, 0.89**	**0.0001**
			–	75	(79.3–12,967) 100	–	**F, 0.69**	**0.01**
		BDE-153	–	7.0 (1.3-154) 100	55.9 (13.2–1352) 100	–	M, 0.00F, 0.02	1.00>0.95
		BDE-209	–	< LOD (<LOD-6) 8	1,482 (425–32,366) 100	–	–	–
9. Karlsson et al. (2007)	Plasma and dust – 13	BDE-47	–	4.09 (<3.38–8.29) 60	25.9 (12.6–160) 100	–	–	–
		BDE-99	–	< 4.10 (all <4.10) 0	57.6 (23.9–194) 100	–	–	–
		BDE-153	–	2.20 (<0.988–3.86) 60	4.7 (2.39–7.10) 100	–	–	–
		BDE-209	–	11.5 (<5.54–17.4) 80	158 (43.9–1,560) 100	–	–	–
		∑PBDE[h]	–	–	–	–	+ve	–
10. Roosens et al. (2009)	Plasma, diet and dust – 9	BDE-153	–	–	–	–	0.16	0.08
		Σtri-hepta[b]	–	1.9 (0.9–7.2)	11.9 (5.3–69.7)	0.01 (<0.001–0.128)	–	ns
		BDE-209	–	–	106 (19.2–588)	0.139 (<0.04–7.750)	–	ns
11. Sahlstrom et al. (2014, 2015)	Serum – 12 Dust – 12	BDE-47	–	0.56 (<0.05–1.9) 100	21 (6.5–460) 96	–	–	ns
		BDE-99	–	0.078 (<0.049–0.49) 46	17 (<0.74–300) 93	–	–	ns
		BDE-153	–	0.95 (0.38–7.8) 100	1.9 (<0.27–77) 41	–	–	ns
		BDE-209	–	0.68 (0.32–9.5) 100	310 (143–310,000) 100	–	–	ns
12. Stapleton et al. (2012)	Serum, dust and handwipes – 11	BDE-47	–	23.3* (<3.0–350) 97	870 (55–24,720) 100	–	0.362	<0.01
		BDE-99	–	6.39* (<1.1–225) 99	919 (8–36,210) 100	–	0.280	<0.05
		BDE-153	–	5.34* (<0.5–83.1) 96	88 (7–3,407) 100	–	0.195	ns
		BDE-209	–	NA* (<6.0–63.8) 17	2,574 (441–76,130) 100	–	–	–
13. Stasinska et al. (2013, 2014)	Serum – 5 Dust – 33	BDE-47	–	3.96[f] (<0.92–191) 98	36.85 (2.55–391) 100	–		
		BDE-99	–	0.88[f] (<0.75–24.4) 58	56.75 (2.93–372) 100	–	Range 0.14–0.25	moderate >0.05
		BDE-153	–	2.26[f] (<0.55–65.4) 99	6.41 (<LOR–59.9) 100	–		
		BDE-209	–	–	415 (<LOR–82,200) 83	–	–	–
14. Toms et al. (2009)	Milk – 35 Dust – 22	BDE-47	4.10 (0.6-12) 100	–	56 (24-434) 100	–	–	ns
		BDE-99	0.85 (0.2-1.9) 100	–	87 (36-862) 100	–	–	ns
		BDE-153	1.20 (0.60-1.90) 100	–	7.4 (1.0-139) 100	–	–	ns

(*continued on next page*)

Table 2 (*continued*)

Study, measure of external exposure	Total number of PBDE congeners analysed	BDE congener	Milk ng/g lw	Blood ng/g lw	Dust ng/g dw	Diet ng/g ww	Correlations	
			Median (range) % detect				r	p
		BDE-209	0.50 (0.30-1.40) 50	–	291 (95-1,585) 100	—	—	ns
15. Watkins et al. (2011, 2012) office	Serum — 8 Dust and handwipes — 37	BDE-47	–	1.1* (<0.5-4.4) 80	697* (37—19,500) 100	—	0.22	0.25
		BDE-99	–	2.5* (< 1.9 - 45.9) 60	915* (<9.4—32,800) 97	—		
		BDE-153	–	5.0* (<0.5 - 173) 97	138* (11—5,970) 100	—		
Main living area		BDE-47	–	1.1* (< 0.5 - 4.4) 80	671* (<4.3—26,100) 97	—	**0.42**	**0.02**
		BDE-99	–	2.5* (< 1.9 - 45.9) 60	647* (<9.4—43,300) 94	—		
		BDE-153	–	5.0* (<0.5 - 173) 97	66* (<1.3—8930) 97	—		
Bedroom		BDE-47	–	1.1* (< 0.5 - 4.4) 80	454* (69—11,200) 100	—	0.49	0.008
		BDE-99	–	2.5* (< 1.9 - 45.9) 60	696* (119—7,410) 100	—		
		BDE-153	–	5.0* (<0.5 - 173) 97	59* (11—963) 100	—		
Vehicle		BDE-47	–	1.1* (< 0.5 - 4.4) 80	765* (38—19,000) 100	—	0.2	0.41
		BDE-99	–	2.5* (< 1.9 - 45.9) 60	1380* (55—25,800) 100	—		
		BDE-153	–	5.0* (<0.5 - 173) 97	125* (6.5—2,230) 100	—		
16. Whitehead et al. (2013, 2015)	Serum — 5 Dust — 22	BDE-47	–	35 (23–110)[d] 98	NA	—	**0.45**	**0.001**
		BDE-99	–	10 (6.5–25)[d] 100	NA	—	**0.39**	**0.006**
		BDE-153	–	8.9 (5.0–46)[d] 96	NA	—	0.1	0.5
17. Wu et al. (2007)	Milk — 12 Dust — 9	BDE-47	13.9 (2–126.6) 100	–	670 (240–14,610) 100	—	**0.74**	**0.006**
		BDE-99	2.4 (0.4–84.3) 100	–	1010 (290–14,800) 100	—	**0.59**	**0.04**
		BDE-153	3.0 (0.4–91.7) 100	–	110 (<LOD–560) 55	—	—	—
		∑PBDE[g]	28.9 (3.9 - 261) 100	–	1,910 (590 - 34,400) 100	—	**0.76**	**0.003**
		BDE-209	<LOD (<LOD–10.9) 24	–	<LOD (<LOD–9,600) 45	—	i	i

ns = reported as not significant.
* = geometric mean reported.
NA = not available.
[a] = ng/kg body weight.
Σtri-hepta[b] = ΣBDE 28, 47, 99, 100, 153, 154, and 183
[c] = LOQ/√2.
[d] = 25th–90th percentile.
[e] = $\sum_8$PBDE.
[f] = estimated total lipids 5.54 g L^{-1}.
∑PBDE[g] = ∑BDE —47, -66, —85, -99, —100, -138, —153, and —154.
∑PBDE[h] = ∑BDE -28, -47, -100, -99, -154 and -153.
[i] = insufficient samples.
LOR = Limit of Reporting.
Entries in **bold** indicate a significant correlation where **p </= 0.05**.

contribution to be 97% of the total exposure and Roosens et al. (2009) reported dietary contributions of 91% to 96% dependant on whether high or average dust ingestion rates were used to calculate the contribution of dust to the total PBDE exposure. Despite the high proportion of total exposure being from diet, neither study found correlation between PBDEs in duplicate diet and internal dose. In studies that gauged dietary exposure from food frequency questionnaires (FFQ), the most frequently reported associations with PBDE body burden were consumption of meat (Cequier et al., 2015; Imm et al., 2009; Sahlström et al., 2015; Wu et al., 2007), dairy products (Cequier et al., 2015; Wu et al., 2007) and fish (Cequier et al., 2015; Imm et al., 2009; Sahlström et al., 2015), suggesting that a vegan diet would help reduce exposure to PBDEs.

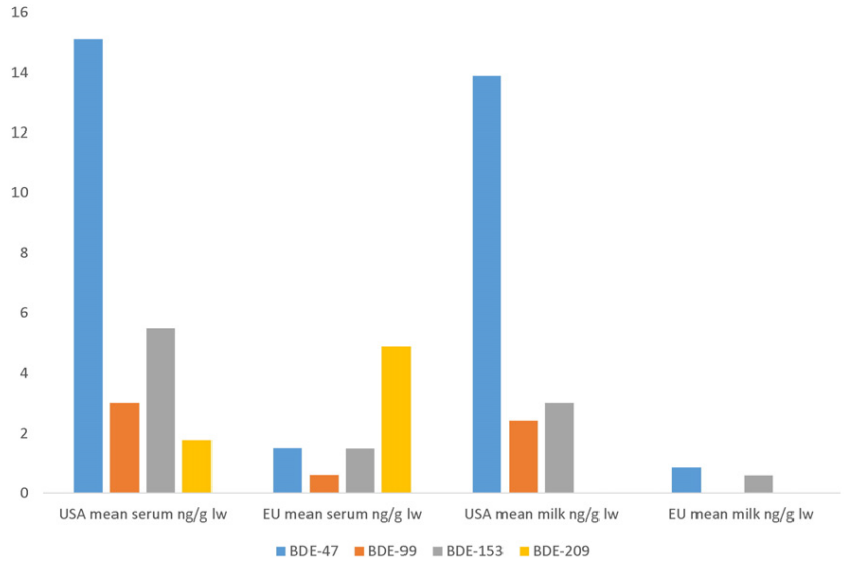

Fig. 2. Mean serum and breast milk PBDE concentrations for included studies for the USA and EU. Means are not directly comparable between studies due to differences in methods and sampling dates.

A number of demographic and anthropometric factors were highlighted as PBDE body burden predictors. Where studies were of women of reproductive age, body burden increased with age (Cequier et al., 2015; Stasinska et al., 2014). Studies including subjects aged 50 and over, as well as young adults, indicated exposure was higher for the younger age groups (Ali et al., 2014; Fromme et al., 2009; Imm et al., 2009). In the Stapleton et al. (2012) study of infants, their body burden also increased with age. Most studies with both male and female subjects did not report whether there was a difference in body burdens between sexes. Fromme et al. (2009) reported no significant difference and Stapleton et al. (2012) reported higher body burden in male toddlers. BDE-153 was found to be negatively associated with body mass index (BMI) (Cequier et al., 2015) and with parity (Stasinska et al., 2014). In the USA, children whose parents had a higher education level had lower PBDE body burdens except for BDE-153. Mothers' education level was positively associated with both length of time breastfeeding and infants' BDE-153 body burden (Stapleton et al., 2012).

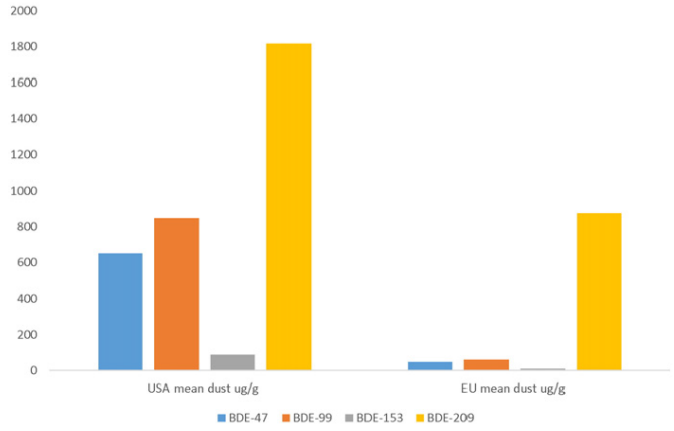

Fig. 3. Mean indoor dust PBDE concentrations for included studies for the USA and EU. Means are not directly comparable between studies due to differences in methods and sampling dates.

3.4. Quality of studies

We rated five of the 17 included studies as being of high quality (Bjorklund et al., 2012; Stapleton et al., 2012; Watkins et al., 2012; Whitehead et al., 2015; Wu et al., 2007), 11 of moderate quality (Ali et al., 2014; Cequier et al., 2015; Coakley et al., 2013; Frederiksen et al., 2010; Fromme et al., 2009; Imm et al., 2009; Johnson et al., 2010; Roosens et al., 2009; Sahlström et al., 2015; Stasinska et al., 2014; Toms et al., 2009) and one of low quality (Karlsson et al., 2007). Frequently observed shortcomings were inadequate sample size and limited demographics of subjects, uncertainties in exposure measurements, non-fasted blood samples, and lack of consideration for confounders.

4. Discussion

This systematic review aimed to assess the current international evidence of the association between PBDE concentrations in diet and indoor environments and diet and human body burden. A total of 17 studies met our inclusion criteria and reported paired human internal and external PBDE concentrations. Generalisation of findings from the individual settings was highly problematic due to the variation across and between studies. The small number of samples in each study limited their statistical power. Nevertheless, both the ubiquitous nature of the exposure and variation with place and time were clearly apparent.

Concentrations of the different PBDE congeners in different matrices, and correlations between them, were influenced by three key factors. Firstly there are regional use patterns and the time of study relative to the phase-out of PBDE technical products. PBDE body burdens in the USA are an order of magnitude higher than those within the EU. In regions where use restrictions of Penta- and Octa-BDE commercial products began earlier, and where their use was less widespread (EU), a different internal congener pattern emerged. Secondly, the human residency period and bioavailability varies greatly between congeners. As BDE-153 is the congener with the longest human half-life, its internal dose concentration increases with time relative to other congeners from the penta-BDE technical mix. Thirdly, the proximity and exposure pathways between the subjects and PBDE sources also vary. The closer the PBDE source is to a receptor and the more frequent and intense their contact is, the stronger their correlation. Exposure pathways

from soft furnishings and electronic items can be ingestion and inhalation of dust, inhalation of vapours and dermal contact. Ingestion and inhalation are the most direct routes of exposure and can be expected to have the strongest effects on body burden. People increase the amount of PBDE available for uptake by their use of the items, i.e. use of a computer keyboard, getting up and sitting down on soft furnishings and opening and closing curtains. Close physical contact between the human receptor and the treated item also provides opportunity for dermal contact. Coakley et al. (2013) suggested that the reason for such strong correlations between mattress dust and serum PBDEs was the amount of time spent in close proximity. Stapleton et al. (2012) hypothesised that their finding of very strong correlation between handwipes and serum for toddlers reflected the increased hand-to-mouth activity of young children and the high proportion of their time spent in the area where their dust samples and handwipes were taken. Bedroom and living room dusts demonstrated stronger correlations with body burden than (non PBDE related) work environments (Ali et al., 2014; Coakley et al., 2013; Watkins et al., 2012). Women on maternity leave and children, demonstrated stronger correlations with PBDEs in their home dust. Ali et al. (2014) suggested that the reason for the stronger correlation between dust and body burden in students than in electronic store workers had to do with the long periods the students spent in their rooms combined with less frequent cleaning.

The number of foam mattresses in a home, and numbers of flat screen TVs, the amount of time spent in the proximity of a working/switched-on TV have all shown associations with PBDE body burdens (Cequier et al., 2015; Dunn et al., 2010; Wu et al., 2007). However, these associations reduce as items containing PBDEs are replaced with new products containing different fire retardant chemicals. Therefore, using counts of domestic electronic equipment to determine PBDE exposure in the home may lead to measurement error (Allen et al., 2008). Environments that were cleaned/dusted more frequently also demonstrated lower correlation with body burden (Ali et al., 2014), indicating that more frequent cleaning may help reduce internal dose. As well as being a major exposure pathway for young children, hand-to-mouth behaviour may also be an important pathway for adults who bite their nails, smoke, or lick their fingers after eating snacks (Cequier et al., 2015). These are all potential opportunities for PBDE ingestion. Dermal absorption may be another pathway, so, not surprisingly, more frequent hand washing was associated with lower PBDE body burden (Watkins et al., 2012).

Dietary exposure to PBDEs may come from the food itself through bioaccumulation in the food chain, or in the case of farmed animal products, it is likely to be the result of contaminated animal feed. PBDE in food may also be the result of processing or packaging. Furthermore, deposition of dusts containing PBDEs onto food during processing or in the place of food consumption may also contribute. The two studies measuring PBDEs in seven day duplicate diets did not find significant correlations with body burdens, and this was interpreted as being the result of low exposure to PBDEs from dietary sources (Fromme et al., 2009; Roosens et al., 2009). Another problem with duplicate diets is that foods with significant PBDE concentrations are collected and mixed together with low or uncontaminated foods and are thereby diluted. Thus the PBDE concentration in the combined sample may fall below the LOQ. We argue that perhaps the average weekly duplicate diet was not a good indicator of non-fasted body burden. Diets analysed may also have consisted of food from such wide varieties of sources that patterns of exposure were not identifiable. It may be that strong congener correlations between diet and body burden only occur where a specific contaminated foodstuff is a regular/major part of the diet e.g. fish from a contaminated lake (Thomsen et al., 2008). Associations were also visible between frequency of consumption of food stuff with higher fat content such as dairy, meat and PBDE body burden (Cequier et al., 2015; Thomsen et al., 2010; Wu et al., 2007). In regions where penta-BDE use has been restricted for longer, penta- and octa-BDEs in body burden are hypothesised to result from diet and the higher brominated congeners from dust exposure (Sahlström et al., 2015).

The findings for the Penta-BDE technical mix congeners, BDE-153 and Deca-BDE technical mix/BDE-209 are sufficiently different to warrant separate summaries for each. Octa-BDE technical mix was primarily used in ABS plastics, often found in business equipment (e.g. fax machines and photocopiers). The included studies did not generally discuss findings in relation to the Octa-mix as it was used less widely in domestic products and therefore home exposure would be limited. Starting with Penta-BDE technical mix (major components BDEs-47,> -99 > -100 > -153), there is strong evidence for dust as an exposure pathway. The Penta-mix, used with polyurethane foam (PUF) and electronics circuit boards (Betts, 2006; Hazrati and Harrad, 2006), has been used much more in North America than the rest of the world and this is reflected in the higher concentrations in home dust and body burdens. The human half-lives for the dominant penta-BDE components, i.e. BDEs-47, -99 and -100 (penta-BDE_3), were estimated to be short (approximately 1-3 years) in comparison to that of BDE-153 (a hexa-BDE) (approximately 12 years or more) (Geyer et al., 2004). Strongly significant correlations between $\sum$ penta-BDE_3 in dusts and body burden were seen in several studies. Intra-congener correlations indicated an ongoing source or sources of the technical mix.

Despite being present in the same technical PBDE mix, fewer significant correlations were reported for BDE-153 (Ali et al., 2014; Coakley et al., 2013). BDE-153 appears to be stored in human adipose tissue more effectively than other congeners, resulting in a longer human half-life. The influence of historic BDE-153 exposures on the internal dose makes the BDE-153 dose much higher than the present dust exposure would suggest. Johnson et al. (2010) reported strong correlation between cohabiting males and females except for BDE-153. BMI appears to be negatively correlated with BDE-153 suggesting that storage of BDE-153 in fat compartments results in dilution in persons with excess adipose tissue (Cequier et al., 2015; Fraser et al., 2009). Weight loss is suggested to increase chemical concentrations in fat tissues (Chevrier et al., 2000; Pelletier et al., 2003). The concentrated BDE-153 present in adipose fat compartments from historic exposures can be mobilised during weight loss. In a study of the milk of 83 women at three and 12 months postpartum, BDE-153 showed a significant increase over time (Daniels et al., 2010). A positive association was seen between length of breastfeeding time and toddlers serum concentrations of BDE-153, which was not seen for other PBDE congeners (Stapleton et al., 2012).

In regions where BDE-209 has been used in substantial quantities, there is no doubt of its ubiquity in dust, usually at much higher concentrations than other PBDEs. This is the result of its greater production volumes and usage. The particularly short residency time of BDE-209, low human bioaccessibility (Abdallah et al., 2012; Fang and Stapleton, 2014) and later use restrictions (if any) explain the differences in findings for BDE-209 from those of the Penta-BDE technical mix congeners. BDE-209 was commonly used for textile coatings and in electronics housings, connectors, plugs and switches. Where successfully measured in human milk, the proportion of BDE-209 of the total PBDE concentration varied from half the total PBDE body burden most recently (Coakley et al., 2013), to much smaller contributions (3.5% and <7% respectively in older studies (Toms et al., 2009; Wu et al., 2007). Although not measured in diet samples for studies included here, BDE-209 has been successfully measured in many foodstuffs (Fernandes et al., 2012). None of the included studies reporting BDE-209 data for both internal dose and dust found significant association between them. This lack of correlation may simply be the result of only recent advances in laboratory capacity for accurate measurement of BDE-209. BDE-209 is ubiquitous in most environments at high concentrations compared with other BDEs. During measurement, BDE-209 adsorbs to a much greater extent than other PBDEs, and is sometimes not recorded. Use of a ^{13}C labelled BDE-209 internal standard allows considerably greater reliability of determination.

So which BDE congener can be expected to be the most toxic to humans? The US-EPA (2010) developed reference dose values (RfD) (estimates of daily oral dose, for a lifetime, likely to be without appreciable risk of deleterious effect) for key PBDE congeners. BDEs-47 and -99 were considered the most potent, both with RfDs of 0.1 μg/kg/day, then BDE-153 at 0.2 μg/kg/day and BDE-209 considerably less so at 7.0 μg/kg/day. EFSA (2011) used a margin of exposure (MoE) approach (the ratio between the safe dose and the estimate of exposure for a population). They concluded that, in Europe, BDE-47, -153 and -209 did not raise health concerns, but that the MoE for BDE-99 in children 1–3 years old was estimated to be below the acceptable MoE of 2.5.

The answer to the question of whether indoor dust exposure or diet is the primary pathway for non-occupational human exposure to PBDE is time- and site-specific. For penta- and octa-BDEs, dietary exposure appears to be similar in both the USA and mainland Europe, so the higher body burdens measured in the USA must be attributable to the higher dust loadings (Frederiksen et al., 2009b). In the two included European studies measuring both dust and dietary exposure, diet was reported to provide over 90% of body burden, despite low dietary PBDE concentrations (Fromme et al., 2009; Roosens et al., 2009). When PBDE sources in the home and workplace are phased out, the proportion of body burden from dietary exposure can be expected to increase for the PBDEs with longer biological half-lives that are found in the food chain, but not for BDE-209.

4.1. Strengths and limitations of included studies

Only one study included their study design (cross sectional and convenience) (Watkins et al., 2012). A general shortcoming was that all studies were from single countries, so differences between regulatory regions were not explored. Extrapolation of participant bio-data to wider populations may be limited given the homogeneous nature of several participant groups. Most of the studies were for a single time point which could be misleading. However, where dust sampling was repeated, the congener proportions were generally found to be similar although loading could change (Frederiksen et al., 2010). The high costs of PBDE analysis, recruitment of study subjects and sample collection may be the reason that many studies are conducted with limited sample numbers.

With higher lipid content than blood, milk samples are a more accurate representation of body burden, although clearly the population for which this observation is possible is limited. Blood has low lipid content, typically e.g. 0.3% to 0.9% (Bramwell et al., 2014), and as PBDEs are stored in blood lipid, analytical laboratory accuracy improves with sample volume. Studies on POPs in human blood generally recommend that fasted samples are taken in order to avoid the influence of recently consumed foods that may give rises to temporary changes in blood levels (Fierens et al., 2003; Nakamoto et al., 2013). However, only one study reported collecting a fasted blood sample (Ali et al., 2014). Internal dose results are usually normalised on a lipid basis according to convention although there is some debate as to whether or not different PBDE congeners in serum are strongly correlated with lipid content (Hakk et al., 2002; Verreault et al., 2007). Most included studies measured lipid in their samples in order to lipid normalise their blood PBDE concentrations, although one did not (Stasinska et al., 2014). The accuracy of blood lipid measurement can also be a large source of measurement uncertainty, as serum lipids are commonly determined by clinical enzymatic methods and approaches to calculate the total lipid content vary between laboratories.

A strength for a number of included studies was that they collected dust samples from a specified floor area and some for a specified time, depending on floor cover, making their results comparable (Ali et al., 2014; Coakley et al., 2013; Roosens et al., 2009). This technique also appeared to give stronger correlations. The study by Coakley et al. (2013) stood out for having so many significant correlations for components of the penta-, octa-, and deca-BDE formulations. Twenty-nine significant correlations (both inter and intra congener) were reported between living room floor dust and milk and 35 between mattress dust and milk. The strongest of these were correlations between mattress dust and milk. These findings highlighted the complexity of inter congener and inter matrix relationships. Correlations between body burden and mattress dust seem plausible given the amount of time spent in close proximity. Correlation between home or office characteristics or contents is limited (Allen et al., 2008) and will become more so as the products containing PBDEs are replaced.

Collection of dietary information is particularly challenging. Study participants may alter their diet when being observed. When duplicate diets are collected by the participant, food items consumed may not always be replicated in the collection vessel. Another issue with duplicate diets is that they reflect only a brief window of time, whereas POPs such as PBDEs, long term dietary habits are also likely to be reflected by body burden. The proportion of influence from short, median and long term dietary exposure is complex including factors such as fasted state and current loss or gain of body fat. FFQs are one method of assessing long-term dietary exposure, however they rely on the participant's memory and estimation of portion sizes (if included). Studies using validated or standard FFQs have found they may not be sufficiently detailed to identify specific PBDE sources (Dunn et al., 2010). Food recall (FR) questionnaires, such as 24 hour FR, provide greater accuracy. New technology may lead to more accurate dietary assessment. Computer programs and smart phone applications are now able to identify foods and approximate weights from photographs and allow less burdensome multiple-pass 24-hour recall e.g. Intake24 (Foster et al., 2014).

Although all but two studies reported BDE-209 concentrations in dust samples (Watkins et al., 2012; Whitehead et al., 2013), only eight of the studies were able to report measurements of BDE-209 in either blood or breast milk. Furthermore, only four studies reported results of correlation analysis for BDE-209. Recoveries of BDE-209 are reported to be considerably higher from dust than serum (Van den Eede et al., 2012; Xie et al., 2010). Sample lipid content has been suggested to negatively influence the recovery of the more highly brominated halogenated flame retardants having high K_{ow} (>9.4) (Cequier et al., 2014b). As such, internal standards with similar K_{ow} (*i.e.* similar recovery) are necessary to prevent underestimation of results, even with well optimised extraction procedures. ^{13}C BDE-209 standard recoveries were rarely reported in the included studies: 13–39% (Karlsson et al., 2007) and mean 64% (Sahlstrom et al., 2014). Frederiksen et al. (2009a) reported the recovery to be low and leading to large uncertainty. Analytical difficulties and measurement uncertainties for BDE-209 were clearly a common limitation.

Only a few studies reported all correlations for all congeners measured. Many presented only a few in the text or stated that no significant correlations were found. If all correlations had been presented, a meta-analysis may have been feasible.

Using the adapted HONEES scheme, only one study was found to be of low quality (Karlsson et al., 2007). The study design and participants were not described, there were only five participants, and laboratory quality control measures did not include standard reference materials (SRMs) or inter-laboratory studies. This was, however, the earliest of the included studies.

4.2. Confounders

Exposure concentrations varied widely between the USA and the rest of the world, and between California and the rest of the USA. There were also differences between urban and rural regions. A country or state's flame retardant regulations affect volumes of use, therefore differences in dates of phase out are limitations for inter-study comparisons. The introduction of multiple replacement flame retardant chemicals for PBDE is a confounder for using numbers of flame retardant containing items in the home as a predictor of dust and serum PBDE loading. Studies with longer time lapse between collection of internal dose and exposure

samples (or *vice versa*) could find confounders being introduced if some everyday exposures had changed. Diet varies between seasons, regions and countries resulting in limitations for inter-study comparison; e.g. populations with high proportions of fish in their diet reflect this in their internal PBDE exposure patterns (Sahlström et al., 2015).

Age of participants also influences body burden. Exposures in infancy (and therefore internal dose) appear to be greater than those for adults. Initially sharing the mother's adult internal dose in utero, during breast feeding the primary exposure pathway is diet, changing to a greater dust exposure which decreases as hand to mouth behaviours reduce (Rose et al., 2010). The 2003–4 American 'National Health and Nutrition Examination Survey' NHANES cohort (n = 1892) found younger adults had higher PBDE levels than the other adult age groups in the study (Fraser et al., 2009). There is evidence that BMI may impact on PBDE body burden, particularly for BDE-153. Fraser et al. (2009) reported that PBDEs tended to increase with decreasing BMI for the NHANES study with highest concentrations measured in the underweight, although this remained significant for only BDE-153 after adjustment for covariates age and race/ethnicity. Although Fromme et al. (2009) (n = 61) found no significant differences in internal dose between male and female adults, Stapleton et al. (2012) found male toddlers to have higher body burdens than females and body burdens were found to be highest among males for the NHANES 2003-4 cohort (Fraser et al., 2009). Depuration of PBDEs in women from pregnancy and lactation period could be a contributing factor in adults (particularly for BDE-153), but for toddlers, differences in activity or other reason/s must have a role. Consistency of postpartum timing of milk collection, time of day, hind milk or foremilk, or complete expression on milk PBDE concentrations could help provide clearer evidence of the depuration effects of lactation (Daniels et al., 2010; Dunn et al., 2010). However, differences in pre-maternity BMI, maternal weight gain, exercise and weight loss will still limit the findings.

Where single time point samples are taken, timing of internal and external exposure measurements may result in confounders. Unusual dietary or dust exposure may be reflected in blood or milk which may not be evident in dust or diet samples from regular external exposure samples or questionnaire. Taking a fasted sample should reduce impact of immediate exposures although it is not ethical/ advisable to request for milk samples or children's blood samples.

Lower income and educational attainment, are indicated as predictors of raised BDE-47 in the USA (Fraser et al., 2009; Rose et al., 2010; Stapleton et al., 2012). This might be the result of different building materials and furniture quality. However, on further investigation, house dust concentrations and condition of foam furniture did not explain disparity of serum penta-BDEs by income (Whitehead et al., 2015; Zota et al., 2008).

Where samples of only dust or only diet were measured, the lack of data on other PBDE sources was reported as a limitation (Stapleton et al., 2012). However, Wu et al. (2007) reported that dust and diet were independent predictors of PBDE body burden. Future studies are encouraged to consider these, and other, factors as possible confounders, as studies included in this review did not have sufficient statistical power to rule them out.

4.3. Strengths and limitations of the review

To the authors' knowledge, this is the first review of correlations between external exposure and human internal dose of PBDEs. An important strength of this study is the adherence to standard systematic review methods. We used validated systematic review methods, exhaustive search techniques, specified inclusion criteria and used the PRISMA checklist to guide reporting essential information from the included studies. A review of current evidence is now timely as sufficient studies have been reported since Karlsson et al. (2007) published their first peer reviewed investigation into correlations between internal and external PBDE.

A major limitation of this review was one person data extraction for the most part. There were several methodological limitations. The exclusion of non-English publications means that potentially relevant articles may have been missed. The exclusion of non-peer reviewed studies excluded an early study of matched milk and dust (Sharp and Lunder, 2004) available only via internet. We did not attempt to search for 'grey literature' which may contain smaller null-result studies that were not accepted for publication. Lastly, the results are limited by the conduct and reporting of the studies from which the data were extracted.

5. Recommendations and conclusions

Our review ascertained that the question of whether dust or diet is the primary human exposure to PBDE may not be possible to answer. To adequately respond to the question would require concurrent international longitudinal investigations, with sufficient statistical power to address the confounders mentioned in Section 4, using consistent methods for sample collection, analytical and statistical analysis and reporting. Different PBDE usage and exposure regions such as North America, mainland EU, the Indian subcontinent and Australasia as well as regions not represented in this review, particularly electronics recycling areas, and historically heavy users such as the UK and Japan should be included.

Technical developments of faster, cheaper extraction of PBDE from biological samples would allow studies to include more subjects. The use of handwipes as a representation of external non-dietary exposure looks promising and should be explored further. As PBDEs, in many instances, have already been replaced by alternative halogenated or organophosphate flame retardants, these should be included where possible in future monitoring. Inclusion of measurements for BDE-209 for all matrices is essential. Reporting using STROBE guidelines would assist inter-study comparability. A considerable body of new research has been undertaken since the 2009 review of human internal and external PBDE exposures (Frederiksen et al., 2009b). An update of this review, including PBDE replacement chemicals may be able to show effects of restrictions on PBDE by replacement of other chemicals.

Our review concluded that there were three key factors influencing the correlation between external and internal PBDE exposure, and three distinct congener behaviours were apparent. Time of study relative to phase-out of PBDE technical products for the country of study, half-life of individual congeners in the human body, and time spent in the location of the source and proximity between PBDE source and study subject were all key factors. Penta-BDE_3 (BDEs-47, -99 and -100), BDE-153 and BDE-209 had distinct exposure patterns. Although penta-BDE_3 and BDE-153 are found in the same technical mix, penta-BDE_3 had much stronger internal - external correlations. The longer human half-life of BDE-153 resulted in an increased proportion of total PBDE body burden which also reflected historic exposures. BDE-209 required a current exposure source to create a significant internal correlation. Because PBDE loading in dust is influenced by discrete sources of PBDE technical mix within the indoor environment, correlations with internal dose were more likely to be detected. Dietary PBDE loading may be from more diffuse sources and dietary exposure is less consistent, so correlation with internal dose is less likely.

Acknowledgements

This study was funded by the UK's Natural Environment Research Council (NERC): CASE studentship NE/F014139/1, the Institute of Health and Society, Newcastle University, UK and the Food and

Environment Research Agency (Fera). Thanks are also given to Mansur Yahaya, Newcastle University, for data extraction duplication.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.envint.2016.02.017.

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2.2.5 Short discussion of strengths and limitations

This was a timely review assessing international evidence from 17 studies of paired PBDE exposure and body burden data. Heterogeneity of studies due to differences in fire prevention regulations, sample collection methods, reported PBDE congeners and correlation reporting meant a meta-analysis was not possible. Nonetheless it provides a succinct and methodical introduction to the field of PBDE exposure and explanation of factors influencing international non occupational human PBDE body burden. The discussion of strengths and weaknesses of the studies should provide a useful introduction to the topic and summary for researchers wishing to undertake BFR exposure and uptake studies themselves.

I used the PBDE body burden predictors indicated in this review to direct the interrogation of PBDE exposure pathways for the paper presented in Section **Error! eference source not found.**. To the best of my ability I also went on to use the recommendations for study conduct and reporting that were one of the outcomes of the study. My understanding of the significance of variations in study design, sample collection, preparation methods and analytical and data analysis all developed greatly as a result of carrying out this review.

2.3 PBDEs and PBBs in human serum and breast milk from cohabiting UK couples

Title: PBDEs and PBBs in human serum and breast milk from cohabiting UK couples.

Authors: Bramwell L, Fernandes A, Rose M, Harrad S, Pless-Mulloli T.

Journal: Chemosphere

Date of publication: April 2014

PBDEs and PBBs in human serum and breast milk from cohabiting UK couples

2.3.1 **Overview**

This paper reports the first measurements of human serum, in the UK, since the 2004 EU ban on all uses of the Penta- and Octa-BDE commercial products and the 2008 EU ban on use of Deca-BDE formulation in electrical applications. These measurements were for ten cohabiting couples selected from 79 completed pre-screening questionnaires to represent a diverse range of PBDE exposures within the financial constraints of available funding. In addition, matched breast milk samples were collected and analysed for females that were nursing infants at the time of the study. The milk concentrations were used to estimate infant PBDE uptake for comparison with health reference values.

PBBs concentrations in serum and breast milk were also measured and reported. PBBs are another group of EU banned brominated flame retardants, neither used nor manufactured in the UK since 1996.

A greater range of PBDE and PBBs were measured than are included in the detailed discussion. All individual measurements are provided in the supplementary data in order that they may be easily utilised in future.

2.3.2 **What was known before**

- Greater amounts of BDE-209 were used in the UK compared with mainland EU to meet the UK's stricter fire safety regulations for soft furnishings, however it was unclear if this had translated into increased BDE-209 body burden in the UK.

- Previous studies of human body burdens, dust and air concentrations and dietary exposures had indicated that use of Penta- and Octa- BDE consumer products in the UK were similar to use patterns in the rest of Europe and a magnitude less than the USA. (Frederiksen *et al.*, 2009).

- Previously published ∑PBDE serum concentrations for UK samples collected in 2003 had range 0.63-420 and median 5.6 ng g^{-1} lipid weight (lw) (Thomas, 2006) with a detection rate of 7% and a limit of detection (LOD) of 15 ng g^{-1} lw for BDE-209.

- Previously published $\sum BDE_{3-7}$ breast milk concentration for UK samples range from 0.2 to 69.0 ng g^{-1} lw (Kalantzi *et al.*, 2004; D'Silva, 2005; Abdallah and Harrad, 2014). Previously reported BDE-209 concentrations in breast milk were 0.1-0.9 ng g^{-1} lw (Abdallah and Harrad, 2014).

- Daily infant intakes of BDEs -47, -99, -153 and -209 for the UK were estimated to be 19.3-14, 4-4.2, 6-6.5 and 1.8 ng kg^{-1} body weight (bw) respectively.

- Measuring concentrations of PBDE in breast milk is more accurate than in the same size serum sample due to its higher lipid content (typically 4% versus 0.5%).

- Serum and breast milk PBDE concentrations are usually presented per lipid weight according to convention and to allow inter-study comparisons. However there is some debate regarding whether different PBDE congeners in serum are strongly correlated with lipid content, BDE-209 certainly appears to undergo partition to proteins and can accumulate in the liver (Hakk *et al.*, 2002; Verreault *et al.*, 2007).

- The accuracy of blood lipid measurement can be a large source of measurement uncertainty, as serum lipids are usually determined by clinical enzymatic methods, and approaches to calculate the total lipid content vary between laboratories.

2.3.3 What the paper added

- I reported post ban $\sum BDE_{3-7}$ serum concentrations of range 1.0 to 16 and median (UB) 4.0 ng g^{-1} lw, for $\sum BDE_{3-7}$ and BDE-209 range <1.2–20 with a detection rate of 15% and LOD of 1.24 ng g^{-1} lw for BDE-209. These findings suggest a modest decrease in median serum PBDE concentrations and a reduction in maximum concentrations since implementation of the EU ban on Penta and Octa BDEs when compared with previously published UK serum PBDE concentrations for 2003.

- Matched breast milk concentrations were 1.3 to 21 ng g^{-1} lw, with median 5.7 ng g^{-1} lw for $\sum BDE_{3-7}$ and range <0.2–1.0 ng g^{-1} lw for BDE-209 (83% detection rate).

- PBB concentrations reported were the first measurements in serum and breast milk for the UK. BB-153 was measurable in 40% of samples with a median concentration of 0.04 and range < 0.01–0.9 ng g^{-1} lw. This was two orders of magnitude below those found in North American and Inuit studies. BB-153 was measurable in 100% of breast milk samples with range 0.06-0.8 ng g^{-1} lw, and $\sum$PBB range in breast milk was 0.06-0.86 ng g^{-1} lw.

- Daily infant PBDE intakes estimated from breast milk concentrations were 17, 5, 5 and 3 ng kg^{-1} bw for BDEs-47,-99,-153 and -209 respectively, all within US-EPA intake guidelines of 100, 100 and 200 ng kg^{-1} bw for BDE-47,-99,and -153 respectively.

Chemosphere 116 (2014) 67–74

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

PBDEs and PBBs in human serum and breast milk from cohabiting UK couples

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HIGHLIGHTS

- UK body burdens of tri to deca PBDE and PBB are reported.
- Paired male and female serum, and female serum and breast milk were measured.
- These are the first UK serum data since EU restrictions on PBDEs.
- A small reduction in median $\sum PBDE_{3\text{-}7}$ UK serum levels are indicated.
- Estimated infant intakes are amongst the highest in the EU for BDEs-47 and -99.

ARTICLE INFO

Article history:
Received 14 November 2013
Received in revised form 10 March 2014
Accepted 12 March 2014
Available online 16 April 2014

Handling Editor: H. Fiedler

Keywords:
PBDE
PBB
Human
Serum
Milk
UK

ABSTRACT

Concentrations of PBDEs and PBBs were measured in matched blood and breast milk samples from 10 UK couples collected in 2011–12. These data are the first measurements in human serum from the UK since the 2004 EU ban on all uses of the penta-and octa-BDE formulations and the 2008 ban on the use of the deca-BDE formulation in some applications. Serum ∑PBDE tri-hepta concentrations ranging from 1.0 to 16 ng g^{-1} lipid weight, with median 4.0 ng g^{-1} lw were measured. Breast milk ∑PBDE tri-hepta concentrations ranged from 1.3 to 21 ng g^{-1} lw, with median 5.7 ng g^{-1} lw. Couples had similar serum congener concentrations unless one of them frequently stayed away from home for work (different diet and dust exposures) or one had occupational exposure to foams and furnishings or electronics. BB-153 were measured above LOD in 40% of sera and 100% of breast milks samples, with median concentrations of 0.04 and 0.06, and maximums of 0.91 and 0.79 ng g^{-1} lw respectively. Concentrations in this study indicated a modest decrease from pre-ban levels reported for the UK. BDE-209 was detected above the limit of detection (LOD) in 15% of sera and 83% of breast milks, with ranges <1.2–20 and <0.2–1.0 ng g^{-1} lw respectively. Average daily infant intakes were estimated at 17, 5, 5 and 3 ng kg^{-1} bw for BDE-47,-99,-153 and -209 respectively, all well below relevant US-EPA threshold reference dose values (RfDs).

1. Introduction

Polybrominated diphenyl ethers (PBDEs) and polybrominated biphenyls (PBBs) are classes of flame retardant that have been used to meet fire safety regulations for fabrics, furnishings, electronics and vehicles since the 1970s. PBDEs are additive flame retardants that are mixed into plastics or foam, or sprayed onto fabrics, without forming chemical bonds with the material. During the use and lifetime of the product, PBDEs may migrate from the material (Sjödin et al., 2003). PBDEs are now ubiquitous in indoor air and dusts (Harrad et al., 2010) and transfer into the wider environment and food chains (Harrad and Diamond, 2006).

PBBs are another group of brominated flame retardants similar in structure, use, manufacture, contamination pathways and toxicological impact to PCBs. Production in the USA ceased following the Michigan Firemaster incident of 1973 where PBB was accidentally introduced into animal feed. Their use as flame retardants in textiles was banned in the EU where they have not been used or manufactured since 1996.

In 1999, Merionyté et al. noted a marked increase in concentrations of PBDEs in the breast milk of Swedish women with levels doubling approximately every four years (Meironyte et al., 1999).This triggered a global interest in human body burden and

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http://dx.doi.org/10.1016/j.chemosphere.2014.03.060
0045-6535/

exposure to PBDEs and investigations into their persistence in humans and the environment. Inhalation and ingestion of indoor dust and food are potential pathways of exposure to PBDEs. Mother to child transfer of PBDEs occurs during breast feeding (Guvenius et al., 2003; Carrizo et al., 2007). Potential adverse human health effects of PBDE exposure and body burden are reproductive toxicity, neurotoxicity and immune effects (Darnerud et al., 2001; Meeker et al., 2009; Gascon et al., 2012; Eskenazi et al., 2013). Evidence of PBDE concentrations in indoor dusts and air in the UK has grown in recent years (Santillo et al., 2003; Harrad et al., 2004, 2006, 2008a,b,c; Harrad and Hunter, 2006; Sjödin et al., 2008a; Harrad and Abdallah, 2011) but few data are available regarding resultant UK human body burdens. It is widely accepted that PBDEs have long half-lives in humans but, even for the same congener, estimates of these values vary widely. There is a general trend of shorter half-lives for the more brominated compounds. Penta- and octa-BDE were banned from use in the EU in 2004 (EU, 2004) with use of deca-BDE in electronics and electrical goods also banned in 2008 (EU, 2008).

1.1. Aim

The aims of this study were to investigate (a) levels of PBDE and PBBs in the sera of co-habiting UK couples, and (b) paired sera and breast milk samples for nursing female partners. Measurements were compared with previous UK data collected prior to the implementation of EU restrictions on the manufacture and use of PBDEs (EU, 2004, 2008). Concentrations of PBDEs in human milk were used to derive estimated infant intakes of tri- to deca-PBDEs.

2. Materials and methods

Paired serum and breast milk samples were obtained from volunteer couples living in the north east of England as part of a wider in-depth study into potential human exposure sources and uptake of PBDE and emerging brominated contaminants. The wider study matches indoor dust and 24 h duplicate diet samples with these serum and breast milks as well as room surveys, diaries and exposure questionnaires, the results of which will be reported later. Sampling was undertaken between April 2011 and February 2012. Ten couples took part in the study and women from six of the couples provided breast milk samples.

2.1. Volunteer recruitment

We aimed to recruit individuals with a range of occupations and diets to reflect low, medium and high exposure to PBDEs, such as workers in electronics, soft furnishings or transport and outdoor workers, oily fish eaters and vegetarians. A short pre-screening questionnaire identified volunteers that would provide the optimum range of exposures. Recruitment was via local universities, local authorities, hospitals, playgroups and breast feeding groups. 79 couples completed the pre-screening questionnaires in 2011. 10 couples were invited, and agreed, to participate in the full study week. Of these 10 couples, two repeated the sampling week as a validation of the method. Inclusion in the study required the participants to be over 18 years of age and to have six months or more of domestic and occupational stability. Volunteers gave written informed consent prior to participation. Ethical approval for the study was provided by the NHS National Research Ethics Committee North East, Durham and Tees Valley, the Newcastle upon Tyne Hospitals NHS Foundation Trust, Newcastle University's Research Ethics Committee and the Food and Environment Research Agency's Ethics Committee.

2.2. Sample collection

Volunteers visited the Clinical Research Facility (CRF) at the Royal Victoria Infirmary at Newcastle to provide 60 mL fasted blood, sampled in the morning of the 8th day of the wider study. Physical measurements, such as body mass index (BMI), were also recorded at the CRF. Where a breast milk sample was provided, $\geqslant$50 mL milk was collected by the volunteer by either pump or manual expression up to 12 h before and 24 h after provision of the blood sample. Blood samples were collected in 6 × 10 mL red-top vacutainers, allowed to coagulate for 20 min, then centrifuged at 1000 rpm to separate the serum which was frozen to −18 °C and stored at the CRF laboratory until analysis. Breast milk samples were collected in Nalgene bottles and stored at −18 °C until transport with the sera samples to the Food and Environment Research Agency (Fera) Laboratories, York, UK for analysis. A set of unused sampling equipment was collected as field blanks in case sample results indicated a potential contamination source, however this was not required. Two couples repeated the sampling week, with sampling points 6.5 and 7.5 months apart. This provided a longitudinal element to the study.

2.3. Laboratory analyses

Details of the methods used for sample preparation, extraction, clean up and analysis of PBDEs and PBBs by high resolution GC MS are described elsewhere (Fernandes et al., 2004 and Fernandes et al., 2008). The performance characteristics of the methodology, including QA parameters such as limits of detection (LODs), precision, linear range of measurement, recoveries etc. have been reported earlier (Fernandes et al., 2008). Further confidence in the data is provided by regular and successful participation in inter-comparison schemes such as POPs in Food 2012 (Bruun Bremnes et al., 2012). The following congeners were measured: BDEs-17, -28, -47, -49, -66, -71, -77, -85, -99, -100, -119, -126, -138, -153, -154, -183 and -209 and PBBs -49, -52, -80, -101, -153 and -209. Lipid determination was carried out by West Yorkshire Analytical Services, Leeds, using the ISO17025 accredited Werner-Schmidt method; acid hydrolysis and solvent extraction.

2.4. Data analysis

Data were normalised to ng g^{-1} lipid for serum and breast milk to enable comparison between matrices and with previous studies. Descriptive statistics were calculated for both lower bound (LB) and upper bound (UB) data, where concentrations <LOD are treated as 0 and the LOD respectively.

2.5. Statistical analysis

Due to the small sample size statistical analyses were mostly descriptive. Statistical analyses were carried out using lower bound data, in keeping with previous UK serum data (Thomas et al., 2006). The analyses used IBM SPSS Statistics for Windows, Version 21.0. Armonk, NY: IBM Corp. Spearman's correlation coefficients were determined between individual and sum congeners and age, BMI, waist-hip ratio, total months breast feeding and parity. The Mann Whitney U test was used to determine any serum differences between males and females, urban and rural inhabitants and different diets.

2.6. Infant intake estimations

Nursing infants' intakes of PBDEs were estimated by multiplying age-appropriate estimated mean daily lipid intakes per kg bodyweight by the lipid weight concentrations of PBDE congeners

for each breast milk sample. The EFSA mean daily intake scenarios used were for a three months old infant (body weight 6.1 kg) with average intake of 800 mL and higher intake 1200 mL. Whole weight PBDE and PBB concentrations were used for the calculations.

2.7. Risk assessment

Estimated BDE-47, -99 and -153 exposures were compared with the corresponding threshold reference dose (RfD) suggested by the US-EPA to determine whether the PBDE infant intakes estimated for this study might be associated with any toxicological endpoints. RfDs are an estimate of oral daily human exposure to a chemical at no-observed-adverse, non-carcinogenic effects levels (NOAEL). For these PBDEs the endpoints considered by the US-EPA are neurodevelopmental toxicological effects. The daily exposures considered were BDE-47 (100 ng kg^{-1}) (US-EPA, 2006b), BDE-99 (100 ng kg^{-1}) (US-EPA, 2006a) and BDE-153 (200 ng kg^{-1}) (US-EPA, 2006c).

3. Results

Serum ∑PBDE tri-hepta concentrations ranged from 1.0 to 16 ng g^{-1} lipid weight (lw), with a median concentration of 4.0 ng g^{-1} lw. BDE-209 was detected above the LOD in 15% of samples, with a maximum of 19.8 ng g^{-1} lw. Breast milk ∑PBDE tri-hepta concentrations ranged from 1.3 to 21 ng g^{-1} lw, with a median concentration of 5.7 ng g^{-1} lw. BDE-209 was detected in 83% of breast milk samples with a maximum of 1.04 ng g^{-1} lw. BDE-47 was usually the most abundant congener present in sera in this study, making up 40% (median) of the ∑PBDE tri-hepta. This was followed by BDE-99 (20%), BDE-153 (9%), BDE-66 (6.5%) then BDE-100 (3.7%) and BDE-49 (2.9%). In samples where BDE-209 was measured above LOD (15% detection rate) this congener comprised 40% (median) of the ∑PBDE. Results for PBDE congener concentrations in individual serum samples from couples 1 to 10 are presented in Fig. 1. Repeat samples for couples 1 and 2 are also depicted. A summary of the serum data (not including repeat samples for couples 1 and 2) and breast milk data is presented in Table 1, including sums of all BDEs measured (∑PBDE), all BDEs measured excluding BDE-209 (∑PBDE tri-hepta), BDE-47, -99, -100, -153, -154 and -183 ($\sum PBDE_{(6)}$), BDEs-47, -99 and -153 ($\sum PBDE_{(3)}$). Individual concentrations are provided in supplementary data (Tables S-1 and S-2). BB-153 was the only PBB detected above the LOD in sera in this study (40% detection rate). BB-153 was detected in 100% of breast milk samples and BB-101 in one sample. PBB measurements are included in Table 1 and both supplementary data Tables S1 and S2.

A significant negative association was found between ∑PBDE in serum and age (Spearman's rho $r = -0.55$, $p = 0.01$), but the association with breast milk and age was not significant ($r = 0.09$, $p = 0.87$). The associations between ∑PBDE in serum and BMI ($r = -0.03$, $p = 0.89$) or body fat mass ($r = -0.07$, $p = 0.78$) were not found to be significant and neither were ∑PBDE in breast milk and BMI ($r = 0.09$, $p = 0.87$). For both congeners BDE-49 and BDE-66 in breast milk, the same significant positive association was noted with BMI ($r = 0.845$, $p = 0.03$). Significant negative associations were found for individual congeners in serum with waist-hip ratio (WHR); BDE-28 ($r = -0.46$, $p = 0.04$); BDE-153 ($r = -0.47$, $p = 0.04$). Parity was found to have a significant negative association with ∑PBDE in females' serum ($r = -0.67$, $p = 0.04$) and serum BDE-153 ($r = -0.69$, $p = 0.03$). Associations between ∑PBDE in breast milk and parity ($r = -0.29$, $p = 0.57$) or total months breastfeeding ($r = -0.26$, $p = 0.62$) were weaker. However, significant negative associations were found between total months breastfeeding and serum BDE-49 ($r = -0.67$, $p = 0.04$). Lipid normalised ∑PBDE data indicated that males had higher PBDE body burdens than their corresponding female partners (7/10 cases). The median concentration of ∑PBDE tri-hepta in males (4.6 ng g^{-1} lipid) was higher than that for females (3.5 ng g^{-1} lipid). However, the difference was only significant for BDE-153 ($p = 0.03$), with a weaker association with BDE-209 ($p = 0.7$). A weak association was found between sera ∑PBDE and having a home in an urban or rural environment ($p = 0.32$). For the two couples who provided two serum samples, differences between PBDE or PBB congener concentrations from the first and second samples were not generally significant, except for increases in BDE-28 ($p = 0.02$) and BDE-47 ($p = 0.04$).

4. Discussion

This 2011/12 study documents UK serum and breast milk data for PBDEs and PBBs. A modest decrease in UK serum PBDE concentrations since the EU bans was found. Compared to earlier studies, participants were recruited from as wide a pool of socio-economic class, occupation, diet and location as possible, with great focus on the detail of information collected for each individual. The small number of participants and the focus on breastfeeding mothers means, however, that results are not representative of all UK residents' exposures.

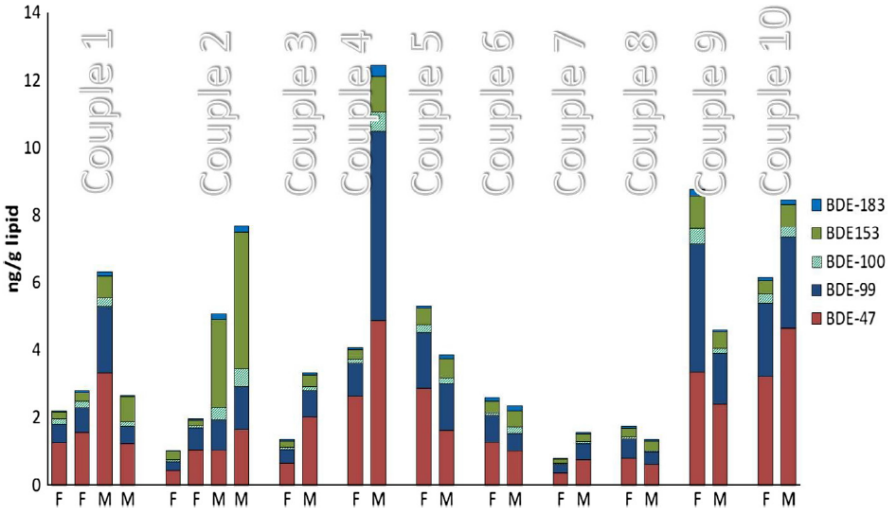

Fig. 1. Individual UK serum PBDE concentrations (ng g^{-1} lw) for congeners with detection rate ⩾50%: BDE-47, -99, -100, -153, -183.

Table 1
Summary of selected[a] PBDE and PBB body burden concentrations for all study participants (ng g^{-1} lw).

Congener	Serum (n = 20)					Breast milk (n = 6)				
	Median		Range		% > LOD	Median		Range		% > LOD
	LB[h]	UB[i]	Min	Max		LB[h]	UB[i]	Min	Max	
BDE-28	0.04	0.12	<0.03	0.55	55	0.09.	0.091.92	0.02	0.31	100
BDE-47	0.63	1.582	<0.36	4.87	60	1.92	1.92	0.32	13.09	100
BDE-49	0.06	0.12	<0.03	0.65	60	0.03	0.03	<0.02	<0.11	67
BDE-66	0.05	0.26	<0.03	0.79	55	0.03	0.03	<0.03	0.13	67
BDE-85	0.02	0.05	<0.02	0.26	50	0.04	0.04	<0.01	0.35	83
BDE-99	0.79	0.79	<0.26	5.61	70	0.88	0.88	0.12	3.74	100
BDE-100	0.15	0.15	<0.03	0.57	80	0.64	0.64	0.07	2.19	100
BDE-153	0.37	0.37	0.12	4.05	100	1.01	1.01	0.70	1.68	100
BDE-138	<LOD	0.07	0.03	0.19	5	0.02	0.02	<0.01	0.04	67
BDE-154	<LOD	0.06	<0.02	0.38	35	0.07	0.07	0.01	0.18	100
BDE-183	0.05	0.07	<0.03	0.33	60	0.05	0.05	0.02	0.23	100
BDE-209	<LOD	3.27	<1.24	19.80	15	0.52	0.54	<0.20	1.04	83
BB-153	<LOD	0.04	<0.01	0.91	40	0.08	0.08	0.06	0.79	100
$\sum$PBDEs[b]	2.41	8.32	2.25	35.41		5.59	5.67	1.28	22.02	
$\sum PBDE_{tri\text{-}hepta}$[c]	2.41	4.03	1.01	15.61		4.76	4.84	1.28	21.03	
$\sum PBDE_{(6)}$[d]	2.23	3.12	0.80	12.82		4.59	4.59	1.25	20.09	
$\sum PBDE_{(3)}$[e]	1.98	2.85	0.73	11.53		3.88	3.88	1.14	5.89	
$\sum PBB_{tri\text{-}hepta}$[f]	<LOD	0.37	<0.04	1.60		0.08	0.17	0.06	0.81	
$\sum$PBB[g]	<LOD	0.74	<0.09	2.27		0.08	0.22	0.06	0.86	
Sample fat %	0.43	0.43	0.25	0.93		2.61	2.61	0.97	4.56	

[a] Where % > LOD is over 15% for either serum or breast milk (BDE-17, -71, -77, -119, -126, and PBB-15, -49, -52, -80, -101, 209 measured but not reported here).
[b] Sum of all PBDE congeners measured.
[c] Sum of all PBDE congeners measured except BDE-209.
[d] Sum of BDE-47, -99, -100, -153, -154 and -183.
[e] Sum of BDE-47, -99 and -153.
[f] Sum of all PBB congeners measured except BB-209.
[g] Sum of all PBB congeners measured.
[h] Lower bound data.
[i] Upper bound data.

The finding of a significant negative association of $\sum$PBDE in serum and age was in line with some previous studies with greater age range of adult participants (Fromme et al., 2009; Garí and Grimalt, 2013; Shi et al., 2013). A non-significant negative association was found with PBDE in serum and BMI in keeping with Jain who found PBDE-153 and PBB-153 to be negatively associated, (Jain, 2013) and in contrast to Fitzgerald et al. who found a significant positive association (Fitzgerald et al., 2010). The present finding that serum BDE-153 was significantly higher for males was in contrast to the two earlier studies of cohabiting couples where gender differences were found not to be significant (Gomara et al., 2007; Fromme et al., 2009).

To the authors' knowledge, the only previous published UK PBDE study is provided by Thomas et al., from samples collected in 2003. This study had 154 participants from thirteen locations across the mainland, including some from the general area of this study. Thomas et al. suggested that their 154 volunteers were not representative of the general UK population as they had a higher proportion of women (68%) and vegetarians (12%) and that sampling on weekdays might select against people in work. They noted that the majority of mothers in their cohort breastfed, which was also found in this study. This study had only one vegetarian (5%). The median age was 37 years (range 26–43), Thomas et al.'s being 41 (range 22–80). The median BMI was 26 (range 22–33) for this study, Thomas et al.'s being 23 (18–43). Technological advances have reduced the LOD for analyses since 2003, most significantly for BDE-209. By considering ratios of data provided by Thomas et al. and the equivalents from this study, indicators of potential changes in UK body burdens were gauged. The data and ratios are presented in Table 2. All median congener concentrations for this study were lower than those reported by Thomas et al. except for BDE-99, where the measurements were very similar. It is likely that significant reductions would take time to manifest due to the long life of PBDE-containing items such as household and office soft furnishings and electronics. The maximum concentrations for individual congeners in 2003 were considerably higher (~50 times) than those in our study (2011/12). The absence of similar high maximum values in this study may indicate a downward shift

Table 2
Comparison of serum PBDE content between UK studies (ng g^{-1} lw).

	Thomas et al. (2006) 2003 data			This study, 2011 data			Ratio medians 2003/2011
	Median LB (ng g^{-1} lw)	Range (ng g^{-1} lw)	% Detects	Median LB (ng g^{-1} lw)	Range (ng g^{-1} lw)	% Detects	
BDE 28	<0.14	<0.14–10	27	0.04	<0.03–0.55	55	
BDE 47	0.82	<0.30–180	68	0.63	<0.36–4.87	60	1.26
BDE 99	0.76	<0.16–150	41	0.79	<0.26–5.61	70	0.96
BDE 100	<0.16	<0.17–390	92	0.15	<0.03–0.57	80	
BDE 153	1.7	<0.26–87	99	0.37	0.12–4.05	100	4.72
BDE 154	0.6	<0.15–4.4	86	<LOD	<0.12–0.38	35	5.45
BDE 183	0.3	<0.14–1.8	55	0.05	<0.03–0.33	60	2.73
BDE 209	<15	<15–240	7	<LOD	<1.24–19.8	15	
$\sum$PBDE	5.6	0.63–420	100	2.408	2.25–35.41	100	3.13
% Fat				0.426	0.25–0.93		

in the distribution of exposure within the UK population, but a more representative study is needed to fully evaluate this hypothesis.

Medians and ranges for BDE-47, -99, -100 and -153 in sera for this study are presented alongside examples from Europe, Asia and North America in Fig. 2. These examples are for studies that include data for men and women together, and where occupational exposure was not targeted. Human body burdens in North America are approximately one to two orders of magnitude higher than those found elsewhere in the developed world. This may be explained by the history of flame retardant regulations in the USA and California in particular (Shaw et al., 2010). The UK has more stringent flame retardant furnishings regulations than mainland Europe (EFRA, 2011) and the highest reported indoor dust BDE-209 concentrations in Europe (Harrad et al., 2008a). However, there is currently no evidence to suggest that penta- BDE use has been any higher in the UK than in mainland Europe. Median results for this study and previous UK figures indicate that BDE-209 and ∑BDEtri to hepta levels sit at the mid to lower end of European data (Thomas et al., 2006; Gomara et al., 2007; Antignac et al., 2009; Frederiksen et al., 2009; Fromme et al., 2009; Roosens et al., 2009). Maximum UK values reported by Thomas et al. are similar to those from the USA, indicating that some UK individuals have had higher PBDE exposure.

To the authors' knowledge, data presented here are the first UK PBB data for both human sera and breast milk. Previous studies with such PBB measurements have often been focused around the Michigan incident and its legacy. General population exposures were sought for comparison with the present results and are shown in Table 3. The median serum BB-153 concentration of 0.04 ng g^{-1} lw (range < 0.01–0.9) for this study, is almost two

Table 3
Median concentrations of BB-153 (ng g^{-1} lw) in human serum samples from different countries.

Location	Year	Number	BB-153	Reference	Note
UK	2011–12	20	0.04 (<0.01–0.9)	This study	(Range)
China	2009–10	21	0.024	Yang et al. (2013)	Geometric mean (gm)
China*	2009–10	35	0.52	Yang et al. (2013)	e waste dismantlers (gm)
Greenland	2002–4	99	1.2	Lenters et al. (2013)	gm
Poland and Ukraine	2002–4	200	<LOQ	Lenters et al. (2013)	
Northwest USA	2004	2062	3.3 (1.4–5.5)	Sjödin et al. (2008b)	NHANES

* Occupationally exposed cohort.

Table 4
Comparison of median (range) PBDE measurements in UK breast milks (ng g^{-1} lw).

Study	Number	Year	Sum PBDE tri-hepta	BDE-209
This study	6	2011–12	5.7 (1.3–21.0)	0.5 (0.2–1.0)
Abdallah and Harrad (2014)	28	2009	5.0 (0.2–26.1)[a]	0.3 (0.1–0.9)
D'Silva (2005)	10 Pooled groups	2000–2	6.4 (0.7–19.3)	
Kalantzi et al. (2004)	54	2001–3	6.6 (0.3–69.0)	

[a] tri-hexa

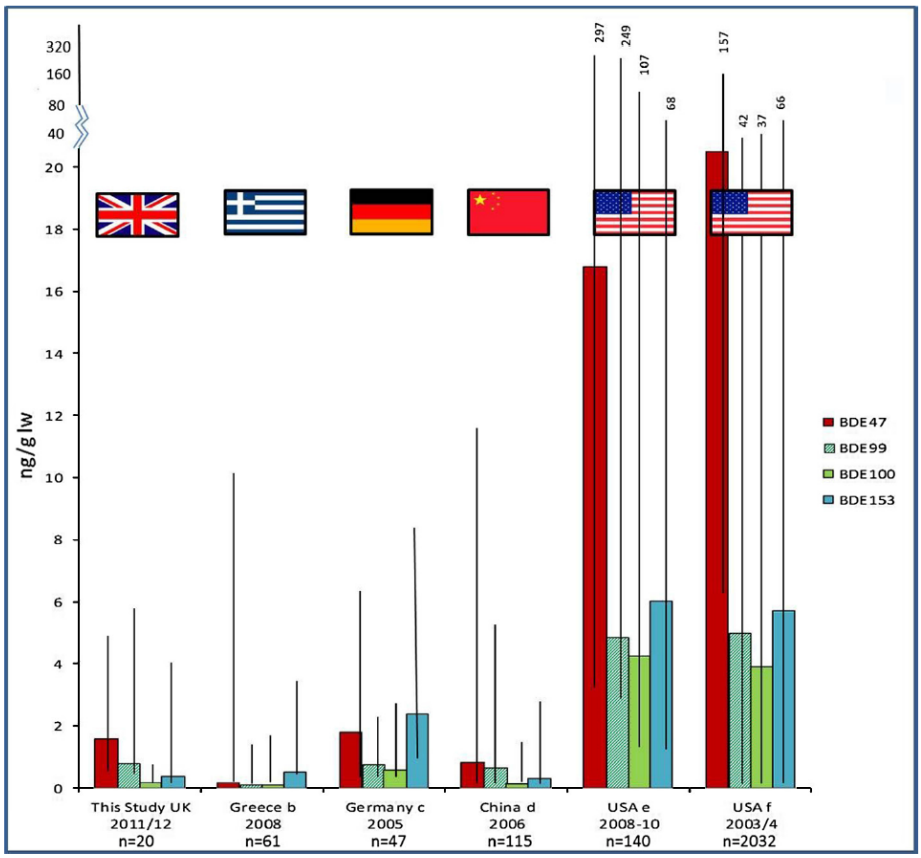

Fig. 2. Median levels and ranges (minimum–maximum) of major PBDE congener concentrations in serum for this and some previous studies of general populations. [b]Kalantzi et al. (2011), [c]Fromme et al. (2009), [d]Zhu et al. (2009), [e]Buttke et al. (2013), [f]Sjödin et al. (2008b).

Table 5
Comparison of mean daily infant intake estimations (ng kg^{-1} bw).

	Average daily consumption scenario 800 mL				High daily consumption scenario 1200 mL			
	BDE 47	BDE 99	BDE153	BDE 209	BDE 47	BDE 99	BDE153	BDE209
UK, This study (n = 6) 2012[a]	17	5	5	3	26	8	8	4
EU, EFSA (24 EU studies)[b]	0.6–14	<0.1–5	0.5–11	1.0–13	1.0–21	<0.1–8	0.7–17	1.0–20
China, Shi et al. (n = 103) 2013[c]				64	41	6	13	1109
NZ, Coakley et al. (n = 33) 2013[d]	11	3	3					
UK, Abdallah and Harrad (n = 28) 2009[e]	19.3	4.2	6.5	1.8				
UK, Kalantzi et al. (n = 54) 2003[b]	14	4	6					

[a] Intakes are calculated for the scenario of a three month old infant weighing 6.1 kg using whole weight breast milk data.
[b] EFSA (2011) Intakes are calculated for the scenario of a three month old infant weighing 6.1 kg and assuming breast milk to contain 3.5% lipid.
[c] Shi et al. (2013) estimated daily maximums and a mean of 64 for BDE-209.
[d] Coakley et al. (2013) estimated daily median exposures.
[e] Abdallah and Harrad (2014) estimated the mean exposure for a 1 month old infant weighing 4.14 kg and consuming 24.4 g lipid day^{-1}.

orders of magnitude below those found in the North American and Inuit studies.

PBDE concentrations in breast milk samples for this study were very similar to the two previous UK studies and current Birmingham UK study (Abdallah and Harrad, 2014). Data for comparison are presented in Table 4. A slight reduction in the median $\sum PBDE_{3\text{-}7}$ may be indicated by the two most recent studies. BDE-209 was measured in 28 breast milk samples collected from women in Birmingham, UK in 2009 with a median concentration of 0.25 and a range <0.06–0.92 ng g^{-1} lw (71% > LOQ) (Abdallah and Harrad, 2014). These are broadly consistent with those reported in this study, where the median concentration of BDE-209 was 0.54 ng g^{-1} lw (range < 0.20–1.04 ng g^{-1} lw).

Although a significant negative association was found with ∑PBDE in females' serum and parity, the association with breast milk was negative but not significant. Of the six women who provided breast milk samples for this study, three were primiparus and three were feeding their second child. Parity has been reported to have a decreasing association with ∑PBDE levels in breast milk (Kang et al., 2010). For all women in the study, total breastfeeding time prior to blood and breast milk sampling for this study ranged from 0 to 60 months, with a median of 10 months. Although a significant negative association was found between total months breastfeeding and BDEs-49 and -153 in females' serum, the negative associations between PBDEs or PBBs in breast milk and breast feeding were not found to be significant. Significant associations were found between BDE-49 and BDE-66 in breast milk and BMI in contrast with earlier studies that found no significant association between BMI and ∑PBDE in breast milk (Chao et al., 2010; Thomsen et al., 2010). The positive association found between age and BDE-153 in breast milk was not significant, although earlier studies have reported that the association is significant (Koh et al., 2010; Lignell et al., 2011) and increased PBDE levels in breast milk with age has been reported (Chao et al., 2010). The breast feeding mothers' median age in this study (35 years, range 27–39) was older than earlier studies by Koh et al. (30.5 years), Lignell et al. (mean 28.7, range 19–41), Chao et al. (30.1, range 22–42), and Kalantzi et al. (range 24–34). In a study of UK breast milk sampled in 2003, the participants were from Lancaster (a small city in rural north-west UK) and London (Kalantzi et al., 2004). Kalantzi et al.'s London participants were found to have higher PBDE body burdens suggesting higher concentrations in individuals residing in larger cities. This study also noted a positive association between breast milk ∑PBDE and urban living, although the difference was not found to be significant.

4.1. Infant intake via breast milk

The infant intake estimations in this study used the average (800 mL) and high (1200 mL) daily consumption scenarios used by the European Food Safety Authority (EFSA, 2011), and are presented in Table 5. Whole weight breast milk PBDE concentrations were used for calculations. EFSA intakes are calculated for the scenario of a three month old infant weighing 6.1 kg and assuming breast milk to contain 3.5% lipid. Lipid content in breast milk samples for this study ranged from 0.97% to 4.56% (median 2.61%). Estimated mean daily infant exposures of BDE-47,-99, -153 and -209 for earlier UK studies and some comparable data from the Europe, China and New Zealand are also presented in Table 4. The estimates in this study are very similar to the most recent UK estimates (Abdallah and Harrad, 2014). BDE-47 and -99 estimates are towards the top end of the EFSA EU data whilst BDE-153 and -209 are more central. The infant intake estimations for BDE-47, -99 and -153 in this study were compared with corresponding US-EPA RfDs. Maximum values for high infant consumption for this study were well within US-EPA guidelines. A NOAEL range of 18.8–41.4 ng kg^{-1} bw for BDE-99 has also been proposed (Bakker et al., 2008). The maximum estimate of daily exposure to BDE-99 (20 ng kg^{-1} bw) in this study is at the low end of this NOAEL. This limited assessment indicates that BDE-47, -99 and -153 in UK breast milk are unlikely to raise health concerns.

5. Conclusions

Evidence of current UK body burdens of PBDEs and PBBs is reported. Although the study is limited in size, it was found that the EU penta- and octa-BDE bans have yet to translate into substantial reductions in internal exposure of the UK population. Little or no reduction in breast milk levels since 2003 has been found.

Acknowledgements

This study was funded by the UK's Natural Environment Research Council (NERC): CASE studentship NE/F014139/1, the Institute of Health and Society, Newcastle University, UK and the Food and Environment Research Agency (Fera). Thanks are also given to the study participants.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.chemosphere.2014.03.060.

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2.3.5 Short discussion of strengths and limitations

This paper provides the first post ban PBDE serum data for the UK and the first UK PBB body burden data.

A combination of the ethical approval required for such studies, and the additional difficulty and expense of extraction and analysis of biological samples whilst avoiding contamination from the laboratory and equipment, particularly for BDE-209 had been major barriers to the research.

The resulting evidence that the greater amounts of Deca BDE product used in the UK had not translated to similarly raised BDE-209 body burdens was welcome even if expected due to chemical characteristics.

The purposive sampling design provided the best opportunity available for the widest range of PBDE body burdens possible from the cohort. A unique exposure story was proposed for each individual by comparing the body burdens between individuals in each couple, whilst also having detailed information on their indoor environments, recent activities, diet and exposure history. This conjecture made an interesting presentation and discussion but was not wholly suitable for an academic paper.

Requesting participants to fast overnight prior to providing their blood sample should have avoided the influence of recently consumed foods that can cause temporary changes in blood PBDE levels. Some of the breast milk samples were collected over a 24-48 hour period and are more likely to demonstrate influence from recently consumed foods as well as perhaps some historic fat deposits being mobilised. Mobilisation of fat deposits may have increased as a result of fasting – although the nursing mothers were instructed not to stick strictly to the fast if hungry. There may have been a little overlap in the duplicate diet sample collection and breast milk sample collection (duplicate diet samples were collected for the 24 hours prior to the blood sample collection) as breast milk collection could commence any time after the duplicate diet collection was completed. A comparison of matched serum and breast milk samples is provided in Section 2.5.4.

With hindsight I would also have asked for the weight of infants that were being nursed during the study period for more accurate infant intake calculations although the volume of milk they were consuming each day would still need to be estimated.

It is difficult to collect uniform breast milk samples suitable for comparison with each other. For this all participants should be feeding their first child and the infants should all be the same age. You also need to be collecting the same part of the feed – there are differences in fat content between start and end of each feed.

I have since used the MOE approach to determine nursing infants' health risk from PBDE exposure as the data used in the derivation of the $BMDL_{10}$ (for neurodevelopmental toxicity) is more recent than that of the US-EPA reference doses – and more conservative. Findings are presented in Table and Table . Using this risk assessment method indicates that even average milk consumption rate for four of the six mother infant pairs studied may be exposing them to potentially concerning levels of BDEs-99, three pairs also indicated concerns for average consumption pf BDE-153. Unfortunately I do not have the infants' weights, but their ages ranged from 1.5 to 8 months.

Table 5. Margins of exposure (MOE) estimated for infants aged 3 months old, weighing 6.1 kg using whole weight breast milk data for this study.

	BDE47	BDE99	BDE153	BDE209
Average daily consumption (800 ml) (ng/kg bw)	17	5	5	3
High daily consumption (1200 ml) (ng/kg bw)	26	8	8	4
MOE for average daily consumption	10.1	0.84*	1.92*	566,000
MOE for high daily consumption	6.61	0.53*	1.2*	425,000

Note *below recommended MOE of 2.5

Table 6. Margins of exposure (MOE) estimated for infants aged 3 months old, weighing 6.1 kg using whole weight breast milk data for this study and $BMDL_{10}$ recommend by EFSA.

		MOEs						
		1F	**2F**	**4F**	**5F**	**9F**	**9F (rpt)**	**10F**
average intake	**BDE-47**	4	77	437	24	16	10	15
	BDE-99	0.3	8.0	32.0	1.5	0.7	0.4	1.3
	BDE153	3.3	4.6	10.5	2.4	1.8	1.6	2.1
	BDE-209	432,000	1,300,000	2,590,000	2,590,000	430,000	216,000	2,590,000
high intake	**BDE-47**	2	51	291	16	11	7	10
	BDE-99	0.2	5.3	21.4	1.0	0.5	0.3	0.9
	BDE153	2.2	3.1	7.0	1.6	1.2	1.0	1.4
	BDE-209	288,000	864,000	1,730,000	1,730,000	288,000	144,000	1,730,000
Infant age (months)		**3**	**5**	**4**	**8**	**1.5**	**1.5**	**4**

Note: shading denotes exposures below recommended MOE of 2.5, the 9F repeat sample was collected the following day

2.4 UK dietary exposure to PCDD/Fs, PCBs, PBDD/Fs, PBBs and PBDEs: comparison of results from 24-h duplicate diets and total diet studies.

Title: UK dietary exposure to PCDD/Fs, PCBs, PBDD/Fs, PBBs and PBDEs: comparison of results from 24-h duplicate diets and total diet studies.

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Journal: Food Additives & Contaminants: Part A

Date of publication: December 2016

2.4.1 **Overview**

This article presents the measurements of several groups of persistent organic pollutants - PBDE, PBB, PCDD/Fs, PCBs and brominated dioxins and furans (PBDD/Fs) - measured in the 24 hour duplicate diet samples collected by the study cohort in the 24 hours prior to them providing their blood and milk samples. The measurements were converted to dietary intake estimations and compared with estimations made using concentrations for individual foodstuffs and national consumption patterns from nationwide UK FSA data. The intake estimations are compared with health reference values for daily PBDE intake. The additional analyses to PBDE and PBB were funded by the UK Food Standards Agency.

2.4.2 **What was known before**

- PCDD/Fs, PCBs and PBB have long been recognised as POPs. Their main human exposure route is via animal and marine fats in the diet. PBDD/Fs have similar sources and properties to PCDD/Fs but have been less studied.

- Foods from higher up the food chain, of animal origin, with a higher fat content (i.e. fish), meat and dairy have higher PBDE concentrations (EFSA, 2011).

- Pre ban estimated $\sum BDE_{3\text{-}7}$ daily average upper bound (UB) dietary intake was 2.2 ng kg^{-1} bw for omnivores and using a seven day DD method for samples collected in 1999/2000 (Harrad *et al.*, 2004).

- Estimates of UK human dietary exposure and health risk assessments for PBDEs and PBDD/F/PBB in 2003/4 were published by the UK FSA (2006) using TDS data and food consumption survey data. The estimated daily average (UB) dietary intakes of 5.8 ng kg^{-1} bw per day for ∑PBDEs and 0.4 WHO 2005 TEQ pg kg^{-1} bw for PBDD/F/PBB. Dioxin and dioxin like concentrations are presented in WHO TEQ equivalences to provide a gauge of relative toxicity. This technique has been further explained in the following paper.

2.4.3 What the study added

- The article documents UK dietary exposure estimates for PCDD/Fs, PCBs, PBDD/Fs, PBBs and PBDEs in the UK in 2011/12 and compares them with health reference intake doses where available.

- Daily UB P97.5 intake estimates for the duplicate diet participants for sum dioxin and dioxin-like analytes (PCDD/F/PCB and PBDD/F/PBB) was 1.4 WHO 2005 TEQ pg kg^{-1} bw, within recommended UK tolerable daily intake of 2 pg WHO 2005 TEQ kg^{-1} bw day^{-1} (COT, 2001).

- Daily UB P97.5 PBDE intake estimates for the duplicate diet participants (BDE-47 = 204, BDE-99 = 263, BDE-153 = 53, BDE-209 = 1770 pg kg^{-1} bw) had MOEs above EFSA derived $NOAEL_{10}$s (BDE-47 = 172,000, BDE-99 = 4,200, BDE-153 = 9.6, BDE-209 = 1,700,000 pg kg^{-1} bw) by the recommended 2.5 times or more (EFSA, 2011). PBDE intake via dust and air must also be considered for total intake estimates (see Section 1.4).

- Combining food diary information with duplicate diet concentrations demonstrated that relative abundance of some individual PBDEs varied between diet types, e.g. BDE-47, -49, -100 and -153 were highest in the duplicate diets containing fish.

- BDE-209 concentrations were consistent across duplicate diet types generating the hypothesis that BDE-209 contamination in diet is coming from non-food sources, i.e. packaging, utensils, or dust contamination.

- The paper provides an in depth comparison of individual dietary exposure estimates using a duplicate diet technique with population based exposure estimates using individual food type measurements combined with national food consumption survey data.

- Findings are presented with international TDS and duplicate diet data for comparison and a graphical figure demonstrates the decrease in adult high (95th and 97.5th percentiles) and average dietary PCCD/F/PCB exposure in Europe over the period 1982–2012.

- The findings and the paper provide an element of validation for both the dietary assessment methods used.

FOOD ADDITIVES & CONTAMINANTS: PART A, 2017
VOL. 34, NO. 1, 65–77
http://dx.doi.org/10.1080/19440049.2016.1258493

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UK dietary exposure to PCDD/Fs, PCBs, PBDD/Fs, PBBs and PBDEs: comparison of results from 24-h duplicate diets and total diet studies

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ABSTRACT

Chemicals in food are monitored to check for compliance with regulatory limits and to evaluate trends in dietary exposures, among other reasons. This study compared two different methods for estimating human dietary exposure to lipophilic persistent organic pollutants (POPs) during 2011/12: (1) the 2012 Total Diet Study (TDS) conducted by the UK Food Standards Agency (FSA) and (2) a 24-h duplicate diet (DD) study of 20 adults from the North East of England. The equivalence of the two approaches was assessed; anything less than an order of magnitude could be considered reasonable and within three-fold (equivalent to 0.5 log) as good. Adult dietary exposure estimates derived from the DD study for both average and high-level (97.5th percentile) consumers compared well with those from the TDS. Estimates from the DD study when compared with those from the TDS were within 10% for P97.5 for total PCDD/F/PCB with divergence increasing to a factor of 3.4 for average BDE-209. Most estimates derived from the TDS were slightly higher than those derived from the DD. Comparison with earlier UK TDS data over the last 30 years or so confirmed a gradual decline in levels of PCDD/F/PCBs in food. Such comparisons also indicated peaks in dietary exposure to ∑PBDE (excluding BDE-209) between 2000 and 2005. Exposure estimates for all measured compounds using both TDS and DD data were found to be within recommended tolerable daily intakes where available or within acceptable margins of exposure.

ARTICLE HISTORY
Received 20 August 2016
Accepted 28 October 2016

KEYWORDS
Duplicate diet study; total diet study; validation; risk characterisation; environmental contaminants

Introduction

Chlorinated dioxins and furans (PCDD/Fs) and polychlorinated biphenyls (PCBs) are recognised persistent environmental contaminants that have been regulated within the European Union (EU) since 2002 (Council Regulation 2375/2001). These regulations were introduced following the 'Belgian dioxins crisis' in 1999 when PCDD/Fs and PCBs were introduced into the food chain via PCB-contaminated animal feed. This resulted in high levels of PCDD/Fs and PCBs in meat products and eggs from Belgian, French and Dutch farms (Bernard et al. 1999) where the feed had been used, and in foods that used products from these sources as ingredients. PCDD/Fs and PCBs accumulate in the food chain, concentrating in the fatty tissue of animals. Diet is the major route of human exposure to PCDD/Fs and PCBs for most individuals without specific occupational exposure. In 2004 an international environmental treaty, The Stockholm Convention, came into force with the aim of eliminating production, use and unintentional release of persistent organic pollutants (POPs) in signatory countries. PCBs and PCDD/Fs were included in the first ratification of the convention, listed in the initial 'dirty dozen' of POPs. In Europe PCDD/Fs and PCBs are regulated in food through Commission Regulation 1881/2006 which sets maximum levels for certain contaminants in foodstuffs. This regulation has been subject to a large number of amendments, some of which relate to limits for dioxins and PCBs (Commission Regulations 565/2008; 420/2011; 594/2012; 1067/2013; 2015/704). A key amendment has been Commission Regulation 1259/2011 which introduced limits for non-dioxin-like PCBs and updated limits for PCDD/Fs and dioxin-like PCBs using 2005 WHO toxic equivalency factors (TEFs).

Brominated dioxins and furans (PBDD/Fs) have similar physicochemical and toxicological properties to their chlorinated analogues (Van den Berg et al. 2013). They originate from similar anthropogenic sources as PCDD/Fs, such as incineration, particularly

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of bromine-containing waste, or chemical manufacture. PBDDs may also have biogenic origin such as photochemical formation from hydroxylated PBDEs (Arnoldsson et al. 2012). Polybrominated biphenyl (PBB) flame retardants are similar to PCBs in structure, manufacture, contamination pathways and toxicological impact on human health, and have some similarities in their use. The use of PBBs as textile flame retardants was phased out from the 1970s onwards and they have not been used or manufactured in the EU since 1996 (D'Silva et al. 2004). PCDD/Fs and dioxin-like compounds bind to the Ah receptor and are widely understood to cause damage to the immune system, to affect the endocrine system, to give rise to reproductive and developmental problems, and may cause cancer (EFSA 2012).

Polybrominated diphenyl ethers (PBDEs) are a class of flame retardant that have been used to meet fire safety regulations for fabrics, furnishings, electronics and vehicles since the 1970s when they were first used as a replacement for PBBs. During the use and lifetime of a product containing PBDEs, they can be released into indoor air and dust (Sjödin et al. 2003) and into the wider environment where they are now ubiquitous (Harrad et al. 2010). PBDEs are persistent, undergo long-range transportation and are found throughout environments and food chains across the globe (Harrad & Diamond 2006). Two commercial PBDE products, penta-BDE and octa-BDE, were added to The Stockholm Convention's list of POPs for elimination in 2009.

Governments and international organisations monitor chemicals in food to evaluate dietary exposures and to protect consumers by ensuring that products entering the food chain are compliant with any applicable regulatory limits (Rose 2015). Total diet studies (TDS) can provide initial exposure estimates for food constituents, such as contaminants, which act as a baseline for any future measures aimed at reducing exposure at the population level. TDS allow exposure time trends to be monitored and in some cases can be used to determine the effectiveness of regulatory controls for different food types, e.g., to assess the impact of pollution control measures on levels of PCDD/Fs in food. An overview of population and population subgroups' exposures to contaminants can be gained using TDS data in which samples of a wide variety of food and beverage types are selected from various retailers across the target area (EFSA, FAO, WHO 2011).

Items are purchased, prepared as if for consumption and combined into groups of similar foods for analysis (EFSA, FAO, WHO 2011; Rose 2015). The food group contaminant concentrations are combined with dietary consumption data to estimate exposure. There are limited historic examples of TDS across the globe, although the approach is gaining popularity. The long-term use of TDS in the UK provides a valuable historic perspective.

Duplicate diet (DD) or duplicate portion studies are useful to provide realistic estimates of an individual's dietary intake over defined periods. Participants collect a duplicate of the food (and sometimes drink) that they consume throughout the defined period, providing a snapshot of their daily diet. The food collected is used to form a composite sample that can be used for analysis. A high degree of cooperation is required from participants. Although the overall composition of the samples will be known, DDs do not attribute exposures to different food groups. DD contents may be influenced by the individual's preferences during the period of collection and subject to anomalies arising where the participant consumes food that is not a regular part of their normal diet. Effects of local contamination and geology or food habits may be noticeable.

The aims of this study were: (1) to investigate dietary exposure to PCDD/F, PCB, PBDD/F, PBB and PBDE for a group of volunteers in the North East of England; (2) to compare the resulting estimates with those made using the UK Food Standards Agency (FSA) TDS 2012 (Fernandes et al. 2012; Mortimer et al. 2013); and (3) to consider risk to human health as a result of the estimated dietary exposures.

Materials and methods

Sample collection

Total diet study (TDS)

The TDS was carried out on foods that represent the average UK diet as estimated by the UK's Department of Environment, Food and Rural Affairs (DEFRA) Expenditure and Food Survey (2011) and trade statistics. Between 1 November 2011 and 31 March 2012, a total of 986 retail food samples were purchased from a range of national supermarkets (50%), symbol retailers (independent retailers that are members of a larger organisation, e.g., Spar) (25%) and independent retailers (25%) in 12 locations around the UK. These samples were split into 20 representative food groups (Table 1) and each food group analysed for a range of contaminants (Henderson et al. 2002). All food groups were analysed except for beverages, which have negligible fat content and therefore have low importance for lipophilic POPs. A wider range of samples was obtained for the animal product food

Table 1. Total Diet Study (TDS) 2012: food group compositions, PCDD/F/PCB and PBDD/F/PBB levels and PBDE congener concentrations (Mortimer et al. 2013).

TDS group	Matrix	Number of subsamples	Fat content (%)	PCDD/F/PCBs (pg WHO 2005 TEQ kg^{-1} ww)		PBDD/F/PBBs (pg WHO 2005 TEQ kg^{-1} ww)		BDE-47 (pg kg^{-1} ww)	BDE-99 (pg kg^{-1} ww)	BDE-153 (pg kg^{-1} ww)	BDE-209 (pg kg^{-1} ww)
				LB	UB	LB	UB				
1	Bread	29	4.14	7.0	11.5	8.2	20.7	5	6	2	< 200
2	Cereals	40	9.42	5.0	12.6	23.1	34.4	6	8	2	< 190
3	Carcass meat	51	14.41	76.7	76.9	29.8	37.0	18	22	7	< 130
4	Offal	85	9.92	191	191	42.0	45.9	7	9	3	< 120
5	Meat products	123	14.86	29.9	30.2	12.0	16.0	18	19	4	< 140
6	Poultry	51	7.32	10.0	10.8	3.0	9.1	5	6	1	220
7	Fish and seafood	140	9.31	326	326	10.5	16.4	134	23	7	170
8	Fats and oils[a]	84	73.8	70.8	91.5	0.0	79.0	37	35	8	< 390
9	Eggs	34	9.55	43.9	44.2	8.4	16.8	13	16	5	90
10	Sugar and preserves	30	6.05	55.5	55.6	94.9	102	121	62	7	1950
11	Green vegetables	23	0.29	4.5	4.6	3.6	6.0	2	1	0.2	50
12	Potatoes	23	5.19	8.1	9.7	9.1	12.6	5	5	1	50
13	Other vegetables	40	5.46	52.6	52.7	4.6	10.1	5	8	1	50
14	Canned vegetables	15	0.53	1.0	2.1	0.6	3.4	1	0	< 1	20
15	Fresh fruit	23	0.21	1.4	3.2	4.0	7.3	1	1	0.2	140
16	Fruit products	15	0.42	6.3	7.5	12.2	16.9	1	1	0.4	30
18	Milk	44	1.97	8.2	8.3	3.5	5.1	2	2	0.5	120
19	Milk and dairy products	102	23.31	105	105	21.7	28.2	23	25	6	20
20	Nuts	34	41.84	5.0	18.8	3.3	34.7	6	5	1	100

Notes: [a]From animal and vegetable origin.
LB, lower-bound data; UB, upper-bound data.

groups, because these are more important sources of POPs in the diet (Fernandes et al. 2012). Table 1 shows the sample numbers for each group. Each individual sample was prepared as though for consumption, using a variety of methods of cooking where appropriate. Samples were homogenised, put into their respective food groups in relative quantities, as determined by national consumption data (PHE 2014), and thoroughly re-homogenised. Aliquots were freeze dried prior to analysis. For intake estimations, total consumption for each food group was derived from 4-day food diaries kept by approximately 500 adult participants (78% aged 19–64 years and 22% aged ≥ 65 years) in the Department of Health's National Diet and Nutrition Survey 2011–2012 (PHE 2014).

Duplicate diet (DD) study

Twenty-four-hour DD samples were collected by 20 volunteers (10 men and 10 women, aged 26–43 years, weight range = 62–101 kg) living in the North East of England as part of a wider in-depth study into potential human exposure sources and uptake of PBDE and emerging brominated contaminants from food and indoor dusts (Bramwell et al. 2014). The wider study matched serum and human milk samples with the 24-h DD samples as well as samples of dust from the volunteers' indoor environments. Two of the volunteer couples subsequently repeated the study providing some validation for the method. The study aimed to recruit individuals with a range of diets potentially to reflect low, medium and high levels of exposure to PBDEs, by selecting participants who were oily fish eaters and vegetarians, and those with possible occupational exposure. A short pre-screening questionnaire identified volunteers who would provide a divergent range of exposures. One female participant was a vegetarian, one had a strong dairy intolerance, one was nursing an infant with a dairy intolerance, two participants ate mainly organic food, and one participant did not eat beef.

The DD samples were collected between 1 April 2011 and 28 February 2012. Whatever food was eaten by volunteers throughout the day, an equal amount was placed into a contaminant-free (this was verified by tests carried out prior to sampling) lidded polypropylene container. Water and water-based drinks were not included. For teas and coffees, the equivalent portion of milk was added. Samples were collected at the end of the day, homogenised immediately and stored frozen in chemically clean (dichloromethane rinsed) glass jars until analysis.

Volunteers gave written informed consent prior to participation. Ethical approval for the study was provided by the NHS National Research Ethics Committee North East, Durham and Tees Valley, the Newcastle upon Tyne Hospitals NHS Foundation Trust, Newcastle University's Research Ethics Committee and the Food and Environment Research Agency's Ethics Committee.

Laboratory analysis

Laboratory analysis for both the DD and TDS samples was undertaken by the Food and Environment Research Agency (Fera) in Sand Hutton, York, UK, and details of the methods used for sample preparation, extraction, clean-up and analysis of PBDEs, PBBs and PBDD/Fs by high-resolution gas chromatography-high-resolution mass spectroscopy analysis are described elsewhere (Fernandes et al. 2004, 2008). Methods for the analysis of PCDD/Fs and PCBs have also been previously reported (Fernandes et al. 2004). The performance characteristics of the methodology, including quality assurance parameters such as LODs, precision, linear range of measurement, recoveries etc. are included in Fernandes et al. (2004, 2008). Further confidence in the data is provided by regular and successful participation in laboratory proficiency testing and intercomparison schemes such as POPs in Food 2011 and 2012 (Bruun Bremnes et al. 2012).

The following congeners were measured in both TDS and DD samples: the seventeen 2,3,7,8-Cl-substituted PCDD/Fs; dioxin-like (i.e., non-ortho-substituted and mono-ortho) PCBs with IUPAC (Favre & Powell 2013) numbers 77, 81, 105, 114, 118, 123, 126, 156, 157, 167, 169 and 189; non-dioxin-like (i.e., ortho-substituted) PCBs with IUPAC numbers 18, 28, 31, 47, 49, 51, 52, 99, 101, 128, 138, 153 and 180; 10 tetra- to hepta-2,3,7,8-Br-substituted PBDD/Fs as well as 2,3,7-triBDD, 2,3,8-triBDF; dioxin-like PBBs with IUPAC numbers 77, 126 and 169; non-dioxin-like PBB-209 and PBDEs with IUPAC numbers 17, 28, 47, 49, 66, 71, 77, 85, 99, 100, 119, 126, 138, 153, 154, 183 and 209. The congeners selected for analysis are those for which reference standards are available. LODs for all measured analytes were estimated dynamically during the specific period of analysis and were dependent on parameters such as sample weight, type of matrix and instrument performance at the time of measurement. Typical LODs were 0.01–0.05 ng kg^{-1} lipid for PCDD/Fs and non-ortho-substituted PCBs; 10 ng kg^{-1} lipid for ortho-PCBs; 0.02–0.08 ng kg^{-1} lipid for PBDD/Fs; and 1–20 ng kg^{-1} lipid for PBDEs and PBBs.

Data treatment and statistics

Dietary exposure assessments for the TDS were carried out using the Intake 2 Programme, bespoke software developed for the FSA. Dietary exposures for average and high-level (97.5th percentile, P97.5) consumers were estimated from the distribution of calculated exposures across all participants. TDS findings for adult average and high-level consumers are used here for comparison with the DD study.

DD daily exposure estimates were calculated from the whole weight (ww) concentration of contaminants in an individual's diet sample multiplied by the mass of sample collected. Individuals' body weights were used to calculate their exposure on a body weight (bw) basis. Where participants repeated the study, only data from their first set of results were included in the statistical analysis. Data for the repeat 24-h DD are included in Table A1 in the supplemental data online. For comparison with the TDS exposure estimates, the average and P97.5 are presented for DD exposure estimates, although P97.5 is not robust for 20 individuals.

Where the analytes are PCDD/Fs or are known to show dioxin-like toxicity, i.e., PCDD/F, PBDD/F, non-ortho and mono-ortho-substituted PCBs and PBBs, the PCDD/F like toxicity of the samples has been reported as toxic equivalence (TEQ) using TEFs, which express the toxicity of each compound relative to 2,3,7,8-TCDD (where 2,3,7,8-TCDD = 1). The most recent, updated WHO 2005-TEQ (Van den Berg et al. 2006) as well as the WHO 1998-TEQ predecessors (Van den Berg et al. 1998) are both used here to allow for direct inter-study comparison. Although derived for PCDD/Fs and dioxin-like compounds, the WHO 2005-TEQ are also used for their brominated analogues (Van den Berg et al. 2013). This is a commonly used (Fernandes et al. 2012; Pratt et al. 2013) interim measure until experimental TEF values for all of the brominated congeners that show dioxin-like toxicity become available (COT 2006). For monitoring and regulation of non-dioxin-like PCBs, the International Council for the Exploration of the Sea (ICES) selected six commonly measured 'indicator' non-dioxin-like (ortho) PCBs 28, 52, 101, 138, 153 and 180 (ICES-6 PCBs) (Webster et al. 2013) and the sum of these is presented here.

Lower bound (LB) results assume that values at < LOD are zero whereas upper bound (UB) results assume that values < LOD are equal to the LOD. Summary exposure estimates are presented as both LB- and UB-contaminant concentrations on a body weight basis. Improvements in measurement sensitivity have led to (1) an increase in LB estimates, (2) a decrease in UB estimates based on lower limits of quantification and (3) convergence of LB and UB estimates. EU analytical regulations for foodstuffs require the difference between UB and LB values to be less than 20% for confirmations of regulatory maximum exceedances (Commission Regulation 589/2014). Summary analyte concentrations discussed in the text use UB values, and are thus precautionary 'worst case' estimates.

Findings are discussed for both lipid weight (lw) and ww contaminant concentrations. The laboratory results are presented as lw data so these values are relevant to the measured fat/lipid content of the sample. The measured fat/lipid content is also provided for each sample for simple conversion to ww where required. Ww values reflect the sample as received whole or 'wet' and is the usual manner of expressing consumption and exposure data. Dietary exposure to POPs from the 'fish and seafood' group is monitored and regulated using ww measurements. Ww measurements provide a more realistic reflection of dietary exposure as the fish group contains many different species of both oily (high lipid content) and white fish (low lipid content). Liver ('offal' group) is also regulated using ww data (EEC 2013) as POPs in liver are also bound to proteins (Huwe 2012). In contrast, foods such as beef or lamb ('carcass meat' group) where different parts of the animal would contain different amounts of fat, and dairy items are monitored and regulated by their lw contaminant concentrations.

Human health-risk characterisation

The sum of dietary exposure to PCDD/Fs and dioxin-like PCBs, PBDD/Fs, and dioxin-like PBBs from the TDS and DD was compared with the tolerable intake value of 2 pg WHO-TEQ kg^{-1} bw day^{-1} (COT 2001) as set by the UK Committee on Toxicology of Chemicals in Food, Consumer Products and the Environment (COT) and in line with current tolerable intakes derived by JEFCA (2001). It should be noted that the COT TDI was set based on PCDD/Fs and dioxin-like PCBs only and did not include PBDD/Fs, and dioxin-like PBBs. Health based guidance values are not available for non-dioxin-like PCBs and PBBs.

Potential health risks from dietary intake of PBDEs were determined using the margin of exposure (MOE) approach applied by EFSA. The EFSA Panel on Contaminants in the Food Chain (EFSA 2011) identified effects on neurodevelopment as the critical endpoint. Chronic human intakes, associated with body burdens at the $BMDL_{10}$ for BDE-47, -99, -153 and -209, were estimated to be 172, 4.2, 9.6 and 1,700,000 ng kg^{-1} bw day^{-1} respectively. Average and P97.5 human dietary intakes as estimated by the DD and TDS methods were compared with EFSA's chronic human daily dietary intake estimations to determine the MOEs. For PBDEs, EFSA consider that an MOE above 2.5 indicates that a health concern is unlikely, with risk decreasing as the MOE increases (EFSA 2011).

Results

POP concentrations in food samples

Detailed results from the 2012 TDS for PCDD/Fs, PBDD/Fs, PCBs, PBBs and PBDEs are provided in Fernandes et al. (2012) and summarised in Table 1. Concentrations for individual congeners in each DD sample, lipid content in each sample and food items making up each sample are presented in Tables A1–A3 in the supplemental data online. Lipid content in the DD samples was median = 5%, range = 2–13%. The DD samples with a low lipid percentage had cups of tea added rather than just the milk. A summary of exposure estimations for the DD samples is presented in Table 2.

PCDD/F and PCB measurements

The TDS food group 'fish and seafood' demonstrated the highest lw levels of all PCDD/F and PCB groups and also the highest ww levels except for sum PCDD/F and sum non-dioxin-like PCBs where the 'offal' and 'fats and oils' groups respectively demonstrated the highest ww concentrations. Comparison of LB sum of PCDD/Fs, PBDD/Fs and dioxin-like compounds measured indicated that the chlorinated analogues were more abundant than the brominated analogues in the higher lipid content food groups containing meats, fish, dairy, eggs and oils (Table 1). PCDD/Fs were measureable in all DD and TDS samples. The most abundant PCDD/F was OCDD although, due to the low TEF, this was not as important in terms of contribution to the TEQ. The most abundant non-dioxin-like PCB in the DD and TDS samples was CB-153. Of the four non-ortho-substituted PCBs, CB-77 was the most abundant in the DD samples and most of the TDS groups except those containing milk where PCB-126 was the most abundant. Concentration ranges (pg kg^{-1} ww) and detection rates for the ICES-6 indicator PCBs in the DD samples were CB-28: < LOD–7.27 (85%); CB-52: < LOD–16.28 (95%); CB-101: < LOD–23.36 (95%); CB-138: 4.98–29.03 (100%); CB-153: 4.89–31.15 (100%); and CB-180: 1.51–9.67 (100%).

PBDD/F and PBB measurements

LB sum PBDD/Fs concentrations in lower lipid content TDS food groups including 'bread', 'cereal', 'potatoes' and 'fresh fruit' were higher than concentrations in their chlorinated analogues (Table 1). The PBDD/F analysis comprised only 12 congeners, including two tri-substituted PBDD/Fs, due to the availability of reference standards. Measuring fewer brominated than chlorinated congeners may influence the relative sum pg WHO-2005 TEQ kg^{-1} ww reported, though the PBDD/Fs measured were mainly those with the higher

Table 2. Daily adult dietary exposure to PCDD/Fs, PCBs, PBDD/Fs, PBBs and PBDEs as determined by 24-h duplicate diet (DD).

		Minimum			Median		Mean		P97.5	
	% > LOD	LB	UB	Maximum	LB	UB	LB	UB	LB	UB
WHO 1998 TEQ pg kg^{-1} bw day^{-1}										
PCDD/F	–	0.028	0.036	0.844	0.129	0.141	0.168	0.177	0.595	0.606
Non *ortho*-PCB	–	0.026	0.028	0.456	0.070	0.069	0.102	0.102	0.329	0.33
Ortho-PCB	–	0.007	0.011	0.084	0.019	0.026	0.021	0.03	0.057	0.071
WHO 2005 TEQ pg kg^{-1} bw day^{-1}										
PCDD/F	–	0.023	0.036	0.76	0.110	0.122	0.147	0.154	0.530	0.537
Non-*ortho*-PCB	–	0.027	0.028	0.456	0.074	0.075	0.106	0.106	0.342	0.344
Ortho-PCB	–	0.007	0.011	0.084	0.019	0.026	0.021	0.03	0.057	0.071
PBDD/F	–	0.004	0.007	0.615	0.060	0.141	0.121	0.199	0.477	0.558
Non-*ortho*-PBB	–	$< 4 \times 10^{-4}$	0.001	0.002	$< 7 \times 10^{-4}$	0.001	1×10^{-6}	0.001	7×10^{-6}	0.002
Sum of 2005 TEQs	–	0.061	0.083	1.92	0.263	0.265	0.395	0.49	1.41	1.51
PBDD/F results pg kg^{-1} bw day^{-1}										
238-TriBDF	75	< 0.013	0.013	0.129	0.037	0.042	0.045	0.057	0.128	0.128
2378-TetraBDF	75	< 0.009	0.009	0.144	0.034	0.039	0.042	0.05	0.125	0.125
23478-PentaBDF	65	< 0.017	0.017	0.339	0.078	0.078	0.087	0.105	0.3	0.3
1234678-HeptabromoBDF	95	n.d.	0.746	14.2	1.58	1.93	3.14	3.31	12.1	12.0
NDL PCBs pg kg^{-1} bw day^{-1} ICES-6[a]	–	0.1	0.137	2.01	0.41	0.41	0.578	0.583	1.78	1.78
PBDE results pg kg^{-1} bw day^{-1}										
BDE-28	75	< 0.001	1.42	21.2	2.63	4.26	4.84	5.76	17.0	17.0
BDE-47	100	23.4	23.4	208	73.4	73.4	91.9	91.9	204	204
BDE-49	60	< 0.002	1.85	53.7	2.75	5.1	7.3	9.02	42.9	42.9
BDE-66	70	0	1.23	38.9	4.31	5.67	6.57	7.83	30.5	30.5
BDE-99	100	24.2	24.2	274	73.1	73.1	99.6	99.6	263	263
BDE-100	100	4.33	4.33	48.6	13.6	13.6	19.2	19.2	46.2	46.2
BDE-153	100	5.35	5.35	57.5	14.1	14.1	19.9	19.9	53.4	53.4
BDE-154	90	< 0.002	1.77	36.9	9.18	9.18	11.2	11.2	32.2	32.2
BDE-183	95	< 0.002	1.92	59.8	10.9	12.0	11.3	14.3	25.6	44.2
Deca results pg kg^{-1} bw day^{-1}										
BDE-209	90	< 0.059	58.6	1850	596	652	708	751	1770	1770
BB-209	15	< 0.018	17.7	185	< 0.037	37	16.7	50.4	148	148
PBDE summary pg kg^{-1} bw day^{-1}										
∑PBDEs[a]	–	154	226	2320	774	966	982	1040	2290	2310
∑PBDE(except 209)[b]	–	63.3	82.5	677	226	247	274	292	635	646
∑PBDE(6)[c]	–	63.3	66.8	590	218	218	253	256	574	574
∑PBDE(3)[d]	–	54.5	54.5	514	182	182	211	211	494	494

Notes: LOD, limit of detection; NDL, non-dioxin like; LB, lower-bound data; UB, upper-bound data; P97.5 = 97.5th percentile.
[a]Sum of all PBDE congeners measured.
[b]Sum of all PBDE congeners measured except BDE-209.
[c]Sum of BDE-47, -99, -100, -153, -154 and -183.
[d]Sum of BDE-47, -99 and -153.

TEFs. The most abundant PBDD/F in the DD samples was 1,2,3,4,6,7,8-heptabromoBDF, measured above the LOD in all but one of the DD samples (median = 2400, range = 810–39,000 pg kg^{-1} lw; median = 126, range = 51–680 pg kg^{-1} ww). These concentrations were higher than those for OCDD, the most abundant PCDD/F in the DD samples. 1,2,3,4,7,8-HexaBDF was the next most abundant PBDD/F though at concentrations over 10 times less. Non-ortho-substituted PBB-77, -126 and -169 and the fully substituted BB-209 were the only PBB congeners measured in the DD samples. These were all below the LOD (average < 2.7 pg kg^{-1} lw) except for BB-209, which was detected in only 15% of samples. Concentrations and detection rates for PBBs were low and measurable in a only a few of the TDS food groups. Ortho-PBB-15, -49, -52, -80, -101 and -153 were analysed in the TDS samples only. The TDS food group 'fish and seafood' demonstrated some low but measureable concentrations. BB-153 was identifiable in the 'milk and dairy', 'poultry', 'meat products' and 'carcass meat' groups. PBBs would not be expected to be found in UK diet samples as evidence indicates European environmental background levels to be low (EFSA 2010).

PBDE measurements

The food groups 'sugar and preserves', and then 'fish and seafood' demonstrated the highest lipid weight sum PBDE concentrations. An atypically high sum PBDE concentration in an individual sample in the composite 'sugar and preserves' group is the most likely explanation for the groups raised sum PBDE result. BDE-47, -99, -100 and -153 were quantified in all DD samples and BDE-209 in 90%. The highest TDS ww concentrations for BDE-47, -153, -99 and -209 were in the 'fish and seafood', 'fats and oils' and 'sugar and preserves' groups respectively.

Dietary exposure estimates for contaminants

TDS exposure estimates for the dioxin-like POP groups and individual PBDE congeners are summarised in Mortimer et al. (2013) and presented in Table 1. A summary of daily adult dietary exposures estimated by the 24-h DD method is provided in Table 2. Results for PBDD/Fs and PBDE congeners are included only where they were measured above the LOD in 50% or more of the samples. Dietary exposure estimates to PBB are not included in Table 2 due to their low detection rate in the DD samples (maximum of 15% for PBB-209). DD participants had average body masses of 77 and 80 kg for women and men respectively, with an average daily food intake of 1.12 kg. Individual participants' body mass measurements and mass of individual DD samples are provided in Table A1 in the supplemental data online. Details of the DD-matched internal exposure/body burden data (serum and human milk) are reported elsewhere (Bramwell et al. 2014) and matched dust data will be reported subsequently.

Adult dietary exposure estimates for average and high level (P97.5) consumers as determined by the TDS and DD studies are presented in Table 3 for comparison. Ratios of average and P97.5 adult exposure estimates for TDS/DD are also provided in Table 3.

PCDD/F and PCB exposure estimates

Agreement between TDS and DD estimates are good when considering the DD group was much narrower than the adult range used to estimate for TDS. Neither method invalidates the other. The average adult dietary exposure to PCDD/Fs and dioxin-like compounds (PCDD/F/PCBs) was estimated to be 0.52 WHO-TEQ pg kg^{-1} bw day^{-1} when using data from the TDS and 0.27 WHO-TEQ pg kg^{-1} bw day^{-1} when using the DD data. The average adult dietary exposure to the non-dioxin-like ICES-6 PCBs was estimated to be 1.80 pg kg^{-1} bw day^{-1} by the TDS and 0.58 by the DD, the estimate derived from the TDS being over three times that derived from the DD.

PBDD/F and PBB exposure estimates

The average adult dietary exposure to PBDD/F and brominated dioxin-like compounds (PBDD/F/PBBs) was estimated to be 0.2 TEQ kg^{-1} bw day^{-1} by both the TDS and DD. The P97.5 adult dietary exposure to PBDD/F/PBBs was estimated to be 0.51 TEQ pg kg^{-1} bw day^{-1} by the DD and 0.56 TEQ pg kg^{-1} bw day^{-1} by the TDS; these can be regarded as equal given the uncertainties involved. The maximum non-dioxin-like DD PBB-209 exposure determined was 180 pg kg^{-1} bw day^{-1}.

PBDE exposure estimates

The average adult dietary exposure to sum PBDE (for all congeners measured except BDE-209) was estimated to be 290 pg kg^{-1} bw day^{-1} using the data from the DD study and the P97.5 was estimated to be 650 pg kg^{-1} bw day^{-1}. BDE-209 was detected above the LOD in 90% of the DD samples, with average daily exposure estimated to be 750 pg kg^{-1} bw day^{-1} and over three times more when using data from the TDS study (2600 pg kg^{-1} bw day^{-1}). This difference probably reflects the large variation in PBDE concentrations in individual samples for the same food types. Where BDE-209 was detected in DD samples it made up a median of 73% of sum PBDE exposure. If BDE-209 was excluded from the sum, BDE-99 and -47 accounted for just over one-third of the total for all congeners measured, at 37% and 36% respectively, followed by BDE-153 (8%), BDE-100 (6%)

Table 3. Adult dietary exposure to PBDEs, PBDD/F/PBBs, PCCD/F/PCBs and ICES-6 PCBs for this and previous studies.

	Sampling year and study type	Statistical summary information		BDE-47 (pg kg^{-1} bw day^{-1})	BDE-99 (pg kg^{-1} bw day^{-1})	BDE-153 (pg kg^{-1} bw day^{-1})	BDE-209 (pg kg^{-1} bw day^{-1})	∑PBDE except 209) (pg kg^{-1} bw day^{-1})	∑PBDE (pg kg^{-1} bw day^{-1})	PBDD/F/PBB (TEQ pg kg^{-1} bw day^{-1})	PCDD/F/PCB (TEQ pg kg^{-1} bw day^{-1})	ICES-6 (NDL PCBs) (pg kg^{-1} bw day^{-1})
UK (this study)	2011 DD (n = 20, 24 h)	Average	Lower	92	100	20	708	274	982	0.2	0.27	0.58
	2012 TDS	Average	Upper	200	140	30	2560	–	–	0.2	0.52	1.84
	2011 DD (n = 20, 24 h)	Average	Upper	92	100	20	751	292	1040	0.2	0.27	0.58
	TDS/DD	Average	Upper	2.2	1.4	1.5	3.4	–	–	1.0	1.9	3.2
	2011 DD (n = 20, 24 h)	P97.5	Lower	204	263	53	1770	634	2290	0.56	0.88	1.77
	2012 TDS	P97.5	Upper	410	250	60	5030	–	–	0.51	1.08	4.88
	2011 DD (n = 20, 24 h)	P97.5	Upper	204	263	53	1770	646	2310	0.56	0.88	1.77
	TDS/DD	P97.5	Upper	2.0	1.0	1.1	2.8	–	–	0.9	1.2	2.8
UK (FSA 2006)	2003/4 TDS	Average	Lower	500	500	100	4500	–	5800	0.1	–	–
		Average	Upper	500	500	100	4500	–	5900	0.4	–	–
		High	Lower	1000	800	200	13,000	–	15,000	0.2	–	–
		High	Upper	1000	800	200	13,000	–	15,000	0.8	–	–
UK (Harrad et al. 2003, 2004)	1999/2000 DD (n = 10o, 5v, 14 days)	Average o	Lower	651	683	45	–	–	–	–	–	–
	2005 DD (n = 50, 7 days)	Average o	Upper	651	694	178	–	2200	–	–	0.73[a]	–
		Average v	Lower	–	–	–	–	–	–	–	1.09[a]	–
		Average v	Upper	–	–	–	–	–	–	–	0.14[a]	–
		Max. o	Upper	1150	2150	186	–	–	–	–	0.53[a]	–
		Max. v	Upper	–	–	–	–	–	–	–	2.22[a]	–
		Median	Medium	161	255	51	–	–	–	–	0.96[a]	–
Germany (Fromme et al. 2009)	2005 DD (n = 50, 7 days)	P95	Medium	340	501	140	–	–	–	–	–	–
	2004/5 TDS	Average	Lower	–	–	–	–	1100	–	0	–	–
Japan (Ashizuka et al. 2007)	2004/5 TDS	Average	Medium	–	–	–	–	–	–	1.58	–	–
	2003/4 TDS	Median	Upper	400	110	–	–	–		–	–	–
Holland (Winter Sorkina et al. 2006)	2003/4 TDS	P97.5	Upper	1100	210	–	–	–	–	–	–	–
	2004 DD (n = 35, 24 h)	Average	n.a.	770	500	–	480	–	–	–	–	–
Holland (Zeilmaker et al. 2008)	2004 DD (n = 35, 24 h)	Maximum	n.a.	3500	2300	–	3300	–	–	–	–	–
	1994 DD (n = 10,24 h)	Average		140	610	–	–	–	–	–	–	–
	1984 DD (n = 10,24 h)	Average		80	300	–	–	–	–	–	–	–
	1978 DD (n = 10,24 h)	Average		570	120	–	–	–	–	–	–	–

Notes: NDL, non-dioxin like; PCDD/F, PBDD/F and dioxin-like concentrations are presented in WHO 2005 TEQ equivalencies unless indicated otherwise; o, omnivore; v, vegan diet.
[a]WHO 1998 TEQ (using 1998 TEFs results tend to be about 10% higher).

Table 4. Comparison of margins of exposure (MOEs) for PBDEs as determined by the DD and TDS methods and European summary MOEs as determined by the EFSA review of European Union evidence (2011).

	BDE-47			BDE-99			BDE-153			BDE-209		
	DD	TDS	EFSA[a]	DD	TDS	EFSA[a]	DD	TDS	EFSA[a]	DD	TDS	EFSA[a]
MOE for average LB dietary intake	1870	–	593	42	–	38	482	–	320	2,400,000	–	–
MOE for average UB dietary intake	1870	860	90	42	30	6.5	482	320	23	2,260,000	664,000	> 97,000[b]
MOE for high LB dietary intake	844	–	156	16	–	14	180	–	137	960,000	–	–
MOE for high UB DD dietary intake	844	420	38	16	17	3.9	180	160	14	960,000	338,000	> 97,000[b]
EFSA estimated intake at $BMDL_{10}$ (ng kg^{-1} bw day^{-1})		172			4.2			9.6			1,700,000	

Notes: [a]EFSA data is P95.
[b]EFSA determined MOE of 97,000 was for children (aged 1–3) which are considered the most sensitive receptor, and did not determine the adult MOE for BDE-209. The adult MOE for BDE-209 can be expected to be greater than that for children.

and BDE-183 (4%). After BDE-209, BDE-47 exposure was found to be next greatest PBDE congener exposure by the TDS and BDE-99 by the DD. Average daily adult dietary exposure to BDE-47 was 92 pg kg^{-1} bw day^{-1} by DD and twice that by TDS at 200 pg kg^{-1} bw day^{-1}. Average daily adult dietary exposure to BDE-99 was 100 pg kg^{-1} bw day^{-1} by DD and 1.4 times that by TDS at 140 pg kg^{-1} bw day^{-1}. Health-risk characterisation MOEs calculated for the DD and TDS exposure estimates are presented in Table 4 along with MOEs determined by EFSA (2011) summarising European dietary exposure for comparison.

Food groups having the greatest contribution to PCDD/F and PCB dietary intake such as 'fish and seafood', 'meat' and 'milk and dairy' generally had either no or low difference between UB and LB sum values, the greatest difference being 7% for poultry, well within the required 20% (Commission Regulation 589/2014). Food groups with lower PCDD/F and PCBs concentrations had more PCDD/F and PCB congener concentrations below the LOD and therefore greater difference between UB and LB sum values. The difference between UB and LB sum WHO 2005-TEQ concentrations of PCDD/F and PCBs in the different TDS food groups ranged from 0% to 73% with a median of 2% and average of 18%. The differences between UB and LB sum WHO 2005-TEQ concentrations of PBDD/F and PBB ranged from 7% to 100% with median of 36% and average of 44%, consistent with the greater number of congener measurements below the LOD. UB and LB sum PBDE concentrations were calculated for the DD samples. Differences of 6% and 1% were observed using sum average PBDE concentrations and sum P97.5 PBDE concentrations respectively.

Discussion

Evaluation and comparison of methods

This 2011/12 study documents UK dietary exposure estimates for PCDD/Fs, PCBs, PBDD/Fs, PBBs and PBDEs and evaluates and compares the findings of two different methods of estimation. We provide estimates of adult dietary exposure for a range of UK and international TDS and DD studies to allow comparison between findings. TDS estimates were generally higher than the DD results for both average and P97.5 but the differences are not substantial considering that two very different approaches were used. With limited participant numbers and timeframes, DD studies measure a snapshot of individuals' exposures and are unlikely to have the range required to represent a general population. The small number of samples in this DD study also limited the statistical power.

For this study, estimates for individual PBDE congeners show good agreement between the TDS and DD studies, providing an element of validation for both methods, e.g., combined PCDD/F and dioxin-like-PCB exposures compare well with dietary exposure estimates average 0.52 and 0.27 and high 1.10 and 0.88 pg kg^{-1} bw day^{-1} for TDS and DD respectively and a TDS/DD ratio of 1.2. Some of the difference may be accounted for by the limited number of DD participants and possibly their lower meat and dairy consumption compared with average UK diets represented by the TDS. In addition, there are known to be behavioural changes for individuals involved with DD exercises (eat less, more health food) and these may also have an impact of reducing the DD exposure estimates (Rose 2015).

Individual BDEs -47, -99 and -153 had an average TDS/DD ratio range of 1.4–2.2 and range of 1.0–2.0 for P97.5. ICES-6 were higher for the TDS with ratios 3.2 (average) and 2.8 (P97.5). Variation between exposure estimates for BDE-209 (TDS/DD ratio average of 3.4, P97.5 2.8) may be influenced by the high TDS result for the 'sugars and preserves' food group, accounting for 50% of total exposure, and 'milk', accounting for 25% of exposure (Mortimer et al. 2013). The 2012 'sugar and preserves' BDE-209 concentration (2.00 µg kg^{-1} ww) was notably higher than that for 2003 (0.39 µg kg^{-1} ww). This may be due to the inclusion of a highly contaminated

sample within the composite. BDE-209 usage has been particularly high in the UK and contamination of a sample during transport or processing cannot be excluded. With 'sugar and preserves' and 'milk' results excluded the exposure estimates for the TDS and DD are close (Mortimer et al. 2013). Where numbers of samples making the food group composite for TDS are low, distortion of results may occur where one or more samples contained atypically high contamination.

While the relative abundance of some individual PBDEs varied between diet types, e.g. BDE-47, -49, -100 and -153 were higher in the DDs containing fish, BDE-209 concentrations were consistent across DD types (lactose free/vegetarian/omnivore/high meat/high fish). We hypothesise that this indicates BDE-209 contamination may be getting into the food subsequent to the primary production stage when most contamination is assumed to occur, e.g., from food packaging, processing/preparation, contamination with airborne dust particles or dust via dermal contact.

Temporal trends

Concentrations of PCDD/F, PCB and PBB in our food supply have declined over the last decade (EFSA 2010, 2012). The reduction in dietary exposures to PCDD/F and PCB is illustrated in Figure 1 with data from this study and other TDS and DD studies from across Europe. Exponential downward curves can be seen from 1982 to 2012 for both average and high consumers. It should be noted that the sensitivity of analytical methods has improved over the time period depicted, allowing more congeners to be positively determined. These changes may affect comparability when assessing temporal trends. In 2011/12 the estimated high level exposure WHO 2005 TEQ total kg^{-1} bw day^{-1} for total PCDD/F and PBDD/F and dioxin-like compounds was estimated to be 1.44 and 1.59 by DD and TDS respectively. In 2001 and 1982 only PCDD/F and dioxin-like PCBs were measured so a direct comparison is not possible, but decreases are nonetheless apparent: 0.11–0.33 WHO 2005 TEQ total kg^{-1} bw day^{-1} since 2001 and 11 WHO 2005 TEQ total kg^{-1} bw day^{-1} since 1982. When compared with UK levels reported in food groups from 2003 (FSA 2006), the LB results have generally increased whilst the UB levels have generally decreased, although the changes are relatively small in absolute terms. This is again likely to reflect improvements in analytical sensitivity rather than a temporal effect.

Data in Table 3 indicate peaks in dietary exposure to BDE-47 and -99 between 2000 and 2005. BDE-153 has also reduced but not quite as quickly, in keeping with its longer half-life in the environment. BDE-209 exposure may still be increasing, but usage was not phased out at the same time as the lower-substituted BDEs and was particularly high in the UK.

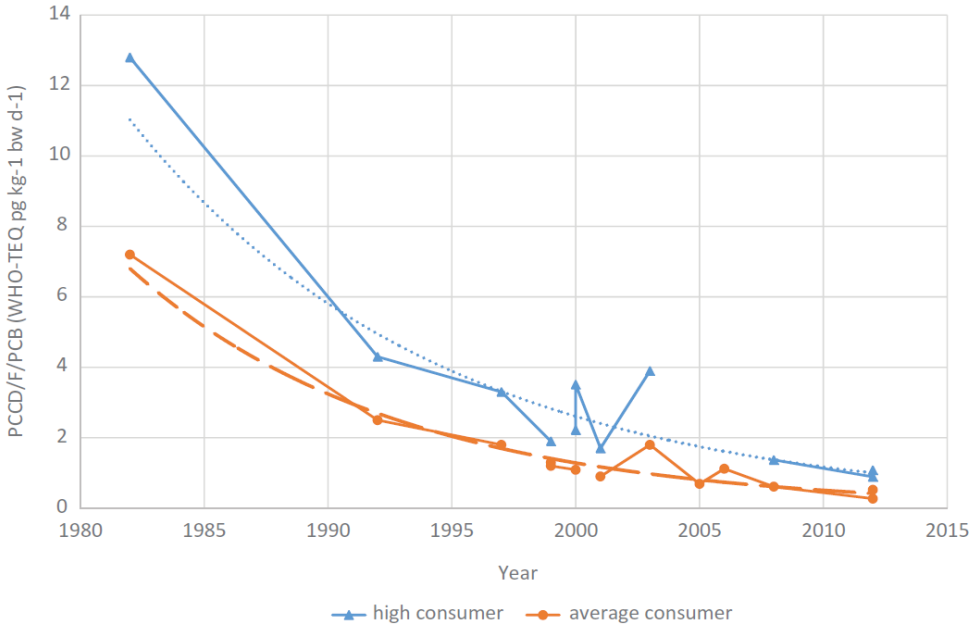

Figure 1. Decrease in adult high (95th and 97.5th percentiles) and average dietary PCCD/F/PCB exposure in Europe, 1982–2012. Data are from UK TDS and DD 2011/12 (this study), UK TDS 1982, 1992 and 1997 (FSA 2003), Netherlands TDS 1999 (Baars et al. 2004), Sweden TDS 1999 and 2005 (Ankarberg et al. 2007), UK DD 1999/2000 (Harrad et al. 2003), Spain TDS 2000 and 2006 (Llobet et al. 2008), France TDS 2001–4 (Tard et al. 2006), and Belgium 2008 (Windal et al. 2010). Exponential curves are fitted to the data.

No temporal influence on exposure estimates would be expected to be measurable between the DD and TDS samples as they were collected in 2011 and 2012 respectively. Comparison of two DD studies carried out in near identical conditions at different periods would be required to investigate such effects.

Risk characterisation

PCDD/F/PCBs and PBDD/F/PBBs

Estimated dietary exposure to PCDD/Fs, PBDD/Fs and dioxin-like compounds for both TDS and DD sample sets for this study, calculated on an UB basis, were within current international recommended tolerable intake values for PCDD/F with dioxin-like PCBs (COT 2001; JEFCA 2001). The DD samples indicated an UB average dietary intake of 0.47 and P97.5 of 1.4 pg WHO 2005 TEQ kg^{-1} bw day^{-1} for PCDD/F/PCB and PBDD/F/PBB. The TDS UB intake estimates indicated an average of 0.77 and P97.5 of 1.6 pg WHO 2005 TEQ kg^{-1} bw day^{-1}. A tolerable weekly intake of 14 pg WHO-TEQ kg^{-1} bw was derived in 2001 by the Scientific Committee on Food (SCF 2001) and a provisional monthly intake of 70 pg kg^{-1} bw was derived by JEFCA (2001). In November 2001, the COT recommended that the UK tolerable daily intake for mixtures of PCDD/Fs and dioxin-like PCBs be reduced from 10 to 2 pg WHO-TEQ kg^{-1} bw day^{-1} (COT 2001).

Non dioxin-like PCBs and PBBs

For non-dioxin-like PCBs, EFSA were unable to derive any health-based guidance values (EFSA 2005). Their recommendation was that dietary exposure should be reduced and data from projects such as this provide a means to determine whether this is being achieved.

To determine the potential for health effects from dietary exposure to sum ortho-PBBs, EFSA use a worst-case no-observed-effect level (NOEL) of 0.15 mg kg^{-1} bw for hepatocarcinogenesis in rats (EFSA 2011). This is six orders of magnitude above the maximum sum ortho PBB exposure determined by the DD study indicating no health concerns. BB-77 was the only non-ortho PBB detected above the LOD in DDs for this study (20% detection rate).

PBDEs

No health concerns are expected from the levels of PBDEs measured in these adult DD and TDS studies as all had MOEs over 2.5 (EFSA 2011). BDE-99 exposures demonstrated the lowest MOEs; 16 and 17 for high UB dietary intake for DD and TDS. EFSA derived an MOE of 3.9 for adults for BDE-99 when reviewing the EU evidence (EFSA 2011). BDE-209 demonstrated the greatest MOE for dietary exposure, 2,260,000 and 664,000 for average UB dietary intake by DD and TDS respectively. These reported MOEs are for adults only, EFSA noted concern about exposure of young children (age 1–3 years) for whom EFSA derived MOEs of 1.4 and 0.7 for dietary exposure to BDE-99 for average and high consumption respectively (EFSA 2011). It should be also be observed that PBDE intake is not exclusively from diet and inhalation and ingestion of PBDEs in indoor dust and air, most notably for BDE-209, will add to total human exposure (EFSA 2011; Bramwell et al. 2016). For adults ingesting 50 mg dust per day this additional BDE-209 source is estimated to be in the range = 0.045–7 ng kg^{-1} bw day^{-1} (Fromme et al. 2009; EFSA 2011). Dust intake is greater for young children and their additional BDE-209 intake from dust estimated to be 0.5–80 ng kg^{-1} bw day^{-1} (EFSA 2011; Bramwell et al. 2016). Both the UK DD and TDS MOEs are well within the UB MOEs determined by EFSA in their review of EU evidence of dietary PBDE exposure (EFSA 2011).

Conclusions

TDS and DD estimations for all measured compounds were found to be within recommended tolerable daily intakes where available or within acceptable margins of exposure. To the authors' knowledge, this study is the first to compare DD and TDS techniques for measuring human dietary exposure to PCDD/Fs, PCBs, PBDD/Fs, PBBs and PBDEs. TDS provide a versatile data set which can be used to estimate dietary exposure for a range of consumers. DD studies give distinct estimates of participating individual's exposures, taking into account local food sources such as farms, fish or wild food. DD are particularly useful for interpreting associations with internal POPs exposure measurements such as serum or human milk concentration. DD studies are difficult to run on a large scale or over a prolonged period of time with issues of cost to individuals and management of sample collection and storage, and may not reflect an individual's long term exposure. The TDS data provided information on the relative levels of contamination in different food groups. When used with food consumption information, the TDS can be used to provide dietary exposure estimates for a range of age groups and eating behaviours making it a more versatile data set. This is particularly useful for establishing baseline levels of population exposure to new contaminants or monitoring temporal changes. By comparing estimates using the two contrasting approaches, both receive an element of cross-validation. There is no doubt that the

DD method is suitable for estimating an individual's dietary intake for the period of the diet collection. It is reassuring to know that the UK national estimate can reasonably reflect individuals' dietary exposure.

Acknowledgements

Thanks are extended to the study participants.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The duplicate diet study was funded by the UK Natural Environment Research Council (NERC) [CASE studentship number NE/F014139/1], the Institute of Health and Society, Newcastle University, the Food and Environment Research Agency (Fera) and the UK Food Standards Agency (FSA).

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2.4.5 **Short discussion of strengths and limitations**

As well as presenting the duplicate diet data for the overarching study, this paper provides a unique validation and detailed comparison of duplicate diet and total diet study dietary intake assessment methods for POPs. The explanations of consequences of use of lower and upper bond data, lipid weight versus whole weight food contaminant concentrations, lowering of limits of detection over time and use of WHO-TEQ values provide helpful insight for interpretation of complex data.

To the authors' knowledge, this study is the first to compare duplicate diet and TDS techniques for measuring human dietary exposure to PCDD/Fs, PCBs, PBDD/Fs, PBBs and PBDEs.

Issues with duplicate diet collection were addition of fruit skin (e.g. banana) or stalks, and sweet wrappers. Participants often opted to collect their food samples on Sunday which can result in a different diet to normal working days.

PBDE intake for the 24 hrs of the duplicate diet collection was measured using whole weight duplicate diet PBDE concentrations multiplied by the mass of DD collected and divided by the weight of the participant to give pg kg^{-1} bw day^{-1}.

2.5 Predictors of human PBDE body burdens for a UK cohort

Title: Predictors of human PBDE body burdens for a UK cohort

Authors: Bramwell L, Harrad S, Abdallah MAE, Rauert C, Rose M, Fernandes A, Pless-Mulloli T.

Journal: Chemosphere

Date of publication: December 2017

2.5.1 Overview

This article presents the matched PBDE indoor dust concentrations for the study cohort. These are examined together with the previously published serum, milk and diet data and information from food frequency and exposure questionnaires, 7 day food and activity diaries and room survey information. The dust concentrations are combined with activity information to estimate dust PBDE intakes for individuals which are then compared with their dietary PBDE intake. Total PBDE intake from dust and diet ingestion is compared with health reference values for daily PBDE intake. Infant intake estimations are also derived for comparison. Food frequency and diary information are combined with body burden data to reveal dietary predictors of PBDE body burden. Room survey information is compared with dust concentrations to reveal predictors of dust PBDE concentrations. The details of the dust sample collection and analysis methods are provided in the supplementary information for this article.

2.5.2 What was known before

- Both dust and diet were known to contribute to PBDE body burden but the range of proportional influence of each for individuals was unclear.

- Previous UK estimations of daily PBDE intakes via dust were mean 53 pg kg^{-1} bw and high 771 pg kg^{-1} bw for $\sum BDE_{3\text{-}7}$ with mean 61,000 pg kg^{-1} bw and high 871,000 pg kg^{-1} bw BDE-209 (Harrad *et al.*, 2008a).

- Penta and Octa BDE use in consumer products in the UK was similar to use patterns in the rest of Europe (Frederiksen *et al.*, 2009). However the higher concentrations of BDE-209 measured in UK dusts indicate that far greater amounts of Deca BDE appear to have been used here (Harrad *et al.*, 2008a; Harrad *et al.*, 2008b).

- The largest contributors to BDE_{3-7} body burden was considered to be from diet. However, it was thought that indoor dust may be a more important source of larger PBDE molecules such as BDE-209 due to their limited bioaccessibility and biomagnification potential.

- Findings from some previous studies of body burden and anthropometrics had found patterns associated with age, BMI and gender (Sjodin *et al.*, 2008) (Toms *et al.*, 2008; Lunder *et al.*, 2010; Stapleton *et al.*, 2012; Whitehead *et al.*, 2015).

- Associations between cleaning frequency, proximity of dust and body burden had been suggested by some previous studies (Wu *et al.*, 2007; Ali *et al.*, 2014; Stasinska *et al.*, 2014).

2.5.3 **What the study added**

- The paper reports average (20 mg dust ingested d^{-1}) and high (50 mg dust ingested d^{-1}) PBDE intakes via dust for our study participants ranging from 13.8 to 1,010 and 35 to 2,520 pg kg^{-1} bw day^{-1} for ∑tri-hepta PBDEs, and 281 to 15,900 and 702 to 39,600 pg kg^{-1} bw day^{-1} for BDE-209.

- $\sum BDE_{3-7}$ intake estimates via dust and diet were found to be similar to previous UK and German intake estimates (Harrad *et al.*, 2008a; Fromme *et al.*, 2009) and an order of magnitude lower than USA estimates (Harrad *et al.*, 2008b).

- Mean BDE-209 intakes from dust for this cohort were found to be an order of magnitude higher than Belgian, German and North American estimates (Harrad *et al.*, 2008b; Fromme *et al.*, 2009; Roosens *et al.*, 2009).

- Findings confirmed that both diet and dust made a contribution to PBDE body burdens and provided new evidence of a substantial range in relative contributions from dust and diet between individuals.

- Intake estimates were again compared with health reference values from EFSA, this time with average and high dust intakes added to the duplicate diet intakes of participants. In addition, proportional infant intakes for the homes were estimated using mean UB dietary intake data from the UK FSA TDS 2012 (Mortimer, 2013), dust concentrations measured in the study and average (50 mg dust ingested d^{-1}) and high (200 mg dust ingested d^{-1}) infant dust intake rates.

- Diet was confirmed to be the primary intake route for congeners found in the Penta BDE commercial mix for the majority of this cohort, with meat being the major contributor.

- Although a reduction in dietary exposure to Penta mix PBDEs since 2002 was indicated, reducing the number of meat portions consumed (without replacing them with fish) would still have the greatest effect on reducing body burdens of Penta mix PBDEs for this cohort.

- Dust was found to be the primary source of BDE-209 for the participants.
- Despite the fundamental importance of room content for its dust-PBDE loading, the study did not find that counts of soft furnishings or electronics could indicate a high or low loading. However, counts of larger PUF furnishings over 20 years old and items adhering to Californian fire safety standard TB117 were important indicators of higher PBDE concentrations in the room's dust.

- For this study the strongest apparent effect on PBDE concentrations in dust was the cleaning frequency. Rooms dusted every week or more had lower PBDE concentrations in their dust.

- The greatest proportion of the estimated dust intake for $\sum BDE_{3\text{-}7}$, BDE-183 and BDE-209 took place in the bedroom (means 43%, 38% and 33% respectively) due in part to the greater amount of time spent in bedrooms. Workplaces and living rooms were the second most important microenvironment for ∑tri-hepta BDEs exposure (mean 19%, 13%) and BDE-183 (20%, 21%)respectively. Vehicles were the second most important microenvironment for BDE-209 intake (20%).

- Diet, occupations and hobbies, home contents, cleaning frequency, BMI and gender all influenced individual internal PBDE dose measurements.

Chemosphere 189 (2017) 186–197

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

Predictors of human PBDE body burdens for a UK cohort

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HIGHLIGHTS

- We report intake and body burdens of tri-hepta BDEs and BDE-209 for 20 UK adults.
- Diet was the major source of tri-hepta BDEs, meat associated with higher exposure.
- Dust was the major source of BDE-209, more frequent dusting reduced exposure.
- Health concerns are indicated for infants with high PBDE intake from dust and diet.

ARTICLE INFO

Article history:
Received 19 June 2017
Received in revised form
11 August 2017
Accepted 12 August 2017
Available online 22 August 2017

Handling Editor: J. de Boer

Keywords:
PBDE
Serum
Breast-milk
Indoor dust
Diet
Exposure

ABSTRACT

Human exposure to polybrominated diphenyl ethers (PBDEs) was investigated in a cohort of 20 UK adults along with their anthropometric covariates and relevant properties such as room surveys, lifestyle, diet and activity details. Selected PBDE congeners were measured in matched samples of indoor dust (n = 41), vehicles (n = 8), duplicate diet (n = 24), serum (n = 24) and breast milk (n = 6).

Combined exposure estimates via dust and diet revealed total PBDE intakes of 104 to 1,440 pg kg^{-1} bw d^{-1} for $\Sigma BDEs_{3-7}$ and 1,170 to 17,000 pg kg^{-1} bw d^{-1} for BDE-209. These adult intakes are well within health reference doses suggested by the European Food Safety Authority (EFSA) and the US EPA. Diet was the primary source of intake of BDE_{3-7} congeners for the majority of the cohort, with dust the primary source of BDE-209. Primary sources of PBDE exposure vary between countries and regions with differing fire prevention regulations. Estimated infant exposures (ages 1.5–4.5 years) showed that BDE-99 intake for one of the households did not meet EFSA's recommended margin of exposure, a further two households had borderline PBDE exposures for high level dust and diet intake.

Males and those having a lower body fat mass had higher serum BDE-153. Higher meat consumption was significantly correlated with higher $BDEs_{3-7}$ in serum. A reduction in dietary $BDEs_{3-7}$ would therefore result in the greatest reduction in BDE-99 exposure. Rooms containing PUF sofas or armchairs over 20 years old had more $BDEs_{3-7}$ in their dust, and rooms with carpets or rugs of that age had higher dust BDE-209. Dusting rooms more frequently resulted in significantly lower concentrations of all major congeners in their dust. Correlation between BDE-209 body burden and dust or diet exposure was limited by its low bioaccessibility. Although vehicle dust contained the highest concentrations of $BDEs_{3-7}$ and BDE-209, serum $BDEs_{3-7}$ correlated most strongly with bedroom dust.

1. Introduction

UK residents are still exposed to a class of potentially harmful brominated flame retardants, polybrominated diphenyl ethers (PBDEs), even though European Union regulations restricting their manufacture, use and importation came into force in 2004 and 2008. Since the 1970s PBDEs have been incorporated into fabrics, foam cushioning and plastics used in everyday items such as vehicles, soft furnishings and electronics. PBDEs slow the rate of ignition and fire growth in petroleum based polymers and resins. PBDEs are not chemically bonded to these materials and are emitted into indoor dust and air through use and volatilisation

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http://dx.doi.org/10.1016/j.chemosphere.2017.08.062
0045-6535/

(Rauert and Harrad, 2015; Sjödin et al., 2003). They can then move into the wider environment where they have been found in sewage sludge, soils and river and lake sediments (Allchin et al., 1999; De Boer et al., 2003; Eljarrat et al., 2008; Harrad et al., 2009). They are persistent organic pollutants as defined by the United Nations Environment Programme's Stockholm Convention and have an environmental half-life of several years. They can travel long distances in the atmosphere and are lipophilic, concentrating in animal and marine fats. These qualities and their wide usage have led them to permeate environments and food chains around the world (Fromme et al., 2016).

A systematic review of human health consequences of exposure to PBDEs concluded health effects may include thyroid disorders, reproductive health effects, and neurobehavioral and developmental disorders (Kim et al., 2014). Evidence of these effects has been seen in animal and *in vitro* research, where the mechanism appears to be altered hormone regulation (endocrine disruption) (Linares et al., 2015; Marchesini et al., 2008; Meerts et al., 2000; Viberg et al., 2006). Exposure during key developmental stages in infancy is most damaging as this is the time when altered hormone regulation will have the greatest impact. Recent estimates of the economic cost of just the intelligence quotient (IQ) points loss and intellectual disability due to PBDE exposure was $266 billion in the USA and $12·6 billion in the EU (Attina et al., 2016). These figures must be balanced against amounts saved due to fire prevention resulting from furnishing flammability standards e.g. £140 million annual savings in the UK estimated by prevention of death, injury and damage to property as a result of Furniture and Furnishings Fire Safety Regulations (1988) that require use of flame retardant chemicals. (BIS, 2009). PBDEs were only one group of flame retardant chemicals from the several BFR groups commonly used to meet such regulations.

In 2004, use of two commercial PBDE products, Penta-BDE and Octa-BDE, were restricted within the EU (European Council Directive 2003/11/EC) and voluntarily phased out in the USA. In 2009, they were added to the Stockholm Convention list of POPs for elimination. Penta-BDE had been primarily used in polyurethane foam (PUF) in soft furnishings, vehicles and printed circuit boards, in greatest amounts in the USA. Furnishings could contain one to four percent Penta-BDE to comply with fire safety regulations (Hammel et al., 2017). The Octa-BDE commercial product has been produced and used less widely than Penta-BDE. Its major use has been in acrylonitrile-butadiene-styrene (ABS) plastics, such as electronics and resin casings of office equipment. The Deca-BDE commercial product has been added to furnishing textiles, and in high impact polystyrene (HIPS) for cables, sockets, mobile phones, fridges and TV housings.

Concentrations of BDE-209 are higher in UK indoor dusts than in dusts from mainland Europe (Frederiksen et al., 2009; Harrad et al., 2008b) as a result of the UK's more stringent fire safety regulations (Furniture and Furnishings Fire Safety Regulations, 1988/1989, 1993 and 2010). Deca-BDE has been restricted from use in electrical and electronic equipment in the EU since 2008 and was added to Annex A of the Stockholm Convention list of POPs in 2017. Both diet and contact with indoor dust constitute important exposure pathways for PBDEs (Abdallah and Harrad, 2014). Foods from higher up the food chain, of animal origin, with a higher fat content (i.e. fish), meat and dairy have higher PBDE concentrations (EFSA, 2011). PBDEs will be circulating in our food chains for many years to come (Harrad and Diamond, 2006), and will be re-circulated back into homes as a result of plastics recycling (Samsonek and Puype, 2013).

Whether dust or diet is the primary exposure source for an individual depends on a number of factors; loading of PBDE in dust or food items and the amounts ingested, whether and when PBDE technical products have been phased out in that country and on the age of the individual (Bramwell et al., 2016). PBDE intake via ingestion and inhalation of dust is the major exposure route for young children in the USA that have frequent hand to mouth behaviours and spend lots of time on floors and carpets (Stapleton et al., 2012). Foetal exposure in the womb and transfer of PBDEs from mother to child during breastfeeding are key exposures for children during important developmental periods. For countries outside of the US and Canada, the largest contribution to tri-hepta BDE body burden is thought to be from diet, especially in regions where Penta-BDE use has been restricted for longer. Dust is likely to be most important contributor to exposure to higher brominated congeners in all regions (Sahlström et al., 2015).

The aim of this study was to determine the major dust and diet sources of PBDEs for a north east England cohort and to consider any potential health risks. The six specific objectives were: (a) to measure PBDE concentrations in dust from homes, work places and vehicles, (b) to calculate relative intake of PBDE via dust in the microenvironments, (c) to evaluate the relative importance of PBDE exposure via indoor dust versus dietary PBDE exposure, (d) to compare intake estimates with reference health values, (e) to investigate relationships between matched environmental and biomonitoring data, and (f) to determine the most effective means of reducing PBDE exposure for the cohort.

2. Materials and methods

We used a cross sectional and subjective sampling strategy to provide a snap shot of PBDE exposures and body burdens for individuals with expected high, average and low exposures. By comparing individuals with expected divergent exposures, we aimed to reveal the factors influencing body burdens.

2.1. Volunteer recruitment

We targeted individuals with a range of occupations and diets; such as workers in electronics, soft furnishings, transport, office workers, outdoor workers, oily fish eaters, omnivores and vegetarians. In 2010/11, following ethical approval for the study, volunteers over 18 years of age and with six months or more of domestic and occupational stability were recruited via local authorities, universities, businesses, hospitals, playgroups and breastfeeding groups. A short pre-screening questionnaire was used to identify volunteers that could provide the optimum range of exposures. 79 couples completed the pre-screening questionnaires, 10 couples were invited, and agreed, to participate in the full study week. Further description of the cohort is provided in the Supplementary Information. Volunteers gave written informed consent prior to participation.

2.2. Timing of sample collection

Participants undertook a 'sampling week' during which they completed an exposure and food frequency questionnaire (FFQ), food and activity diaries, room surveys including contents, usage and cleaning information and they were asked not to vacuum or dust their home. We adapted the validated WHO-IARC EPIC semi-quantitative dietary questionnaire for the study. On the seventh day of their sampling week, participants collected their duplicate diet samples (DD), and the researcher visited that evening to collect the DD samples, home and vehicle dust samples, questionnaires and surveys. The participants then fasted until their blood sample collection appointment the following morning where anthropometric measurements were also taken. Two couples repeated the

full sampling week, with sampling points 6.5 and 7.5 months apart. This provided a longitudinal dimension to the study and an element of validation. All sampling weeks took place between April 1st 2011 and 28th February 2012.

2.3. Duplicate diets, serum and breast milk

Study participants collected an equal amount of whatever food they ate throughout the day in a contaminant free (verified by tests carried out prior to sampling) lidded polypropylene container for the 24 h duplicate diet collection. The next day they provided a fasted 60 ml blood sample at the Clinical Research Facility of the Royal Victoria Infirmary in Newcastle. 50 ml breastmilk samples were collected by either pump or manual expression up to 12 h before and 24 h after provision of the blood sample and kept in pre-cleaned Nalgene containers. Samples were stored at −18 °C until transfer to the laboratory for analysis. Details of the serum, human milk and duplicate diet sample collection and analysis have been published previously (Bramwell et al., 2014; Bramwell et al., 2017).

2.4. Dust samples

Participants were requested not to vacuum or dust their home or vehicle during the sampling week. Dust samples from main living areas (n = 11), bedrooms (n = 12), and vehicles (n = 8) were collected by the researcher following a standard sampling protocol to allow direct comparison with previous studies (Abdallah and Harrad, 2009; Coakley et al., 2013; Harrad et al., 2008a; Harrad et al., 2008b). Samples from workplaces (n = 10) were collected during the sampling week at the participants' (and their employers') convenience. Dust samples were extracted and analysed at the University of Birmingham, UK, using previously published methods for preparation, extraction, clean up, analysis and quality control (Abdallah et al., 2009; Harrad et al., 2008a; Harrad et al., 2008b). Further details of the dust sample collection, preparation, extraction and analysis are provided in the Supplementary Information.

2.5. QA/QC

For the analysis of serum, breast milk and duplicate diet samples, the performance characteristics of the methodology, including quality assurance parameters such as limits of detection (LODs), precision, linear range of measurement, recoveries etc. are included in the previous reports (Fernandes et al., 2008; 2004). Further confidence in the data is provided by regular and successful participation in laboratory proficiency testing and inter-comparison schemes such as POPs in Food (2011 and 2012). PBDEs with IUPAC numbers 17, 28, 47, 49, 66, 71, 77, 85, 99, 100, 119, 126, 138, 153, 154, 183 and 209 were measured. The congeners selected for analysis are those for which reference standards are available. Typical LODs were 1–20 ng kg^{-1} lipid for PBDEs.

For the dust sample analysis the average blank (including field blanks) plus 3 standard deviations was used for the limit of detection giving an average 0.7 ng g^{-1} for $BDEs_{3-7}$ (range 0.2–1.7) and 52 ng g^{-1} for BDE-209. The PBDE ^{13}C labelled internal standard recoveries were: ^{13}C-BDE 47 = 69 ± 20%, ^{13}C-BDE 99 = 70 ± 20%, ^{13}C-BDE 153 = 69 ± 20% and ^{13}C-BDE 209 = 17 ± 6%. The low recovery for BDE-209 indicates uncertainties in its measurement which are presented here with that caveat. Measurement of SRM NIST 2585 had range 78% (BDE-47) to 122% (BDE-49) and mean 100% of the certified contents.

2.6. Exposure assessment

Concentrations of the PBDEs detected in milk and serum samples were lipid-adjusted to allow comparison with the literature. PBDE intake for the 24 h of the duplicate diet collection was measured using whole weight duplicate diet PBDE concentrations multiplied by the mass of DD collected and divided by the weight of the participant to give pg kg^{-1} body weight day^{-1}.

PBDE intakes via dust were estimated by combining measured dust PBDE concentrations with occupation time for individual's various microenvironments (taken from their activity diary) using both average (20 mg/day) and high (50 mg/day) adult dust intake rates average and high adult dust ingestion as estimated by Jones-Otazo et al. (2005). Although dust ingestion rates may differ between microenvironments and activities (as well as individuals), for the purpose of this study, we have assumed that dust ingestion occurred pro-rata to the proportion of time spent in each microenvironment during the study week. This was considered the only practical approach in the absence of data to confirm any differences (Abdallah and Harrad, 2009). For time periods when participants were in their home but not in one of the microenvironments measured, the median of their home dust PBDE concentration was used. For time periods when they were in an indoor environment but not in their own home the median of all dusts collected for the study was used. Time spent outside was not assigned a PBDE concentration. Intake rates via dust were divided by the participant's weight to give pg PBDE intake kg^{-1} body weight day^{-1}.

PBDE intakes for average and high dust intake scenarios: average 20 mg d^{-1}, high 50 mg d^{-1} (Jones-Otazo et al., 2005) and diet intakes determined from the 24 h duplicate diet concentrations were added together for comparison with the European Food Safety Authority's (EFSA) chronic human daily dietary intake estimations to determine the margins of exposure (MOEs). As PBDE exposure during infancy is considered to present a greater risk to health than that for adults, estimated average and high exposure scenarios for infants aged 1.5–4.5 years old were developed as well. Daily average (50 mg d^{-1}) and high (200 mg d^{-1}) dust intake estimations (Jones-Otazo et al., 2005) per kg body weight were extrapolated from individual adult intake values determined for the study. These were added to average and high dietary PBDE intake estimations from the UK total diet study (TDS) (2012) data for infants aged 1.5–4.5 years old. Risk assessment for infants from PBDE in breast milks collected for the study has been previously reported (Bramwell et al., 2014).

2.7. Data analysis

Associations between PBDE concentrations and intakes and potential predictors were explored with scatter plots, box plots and correlations using IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp, Minitab 17 and Excel (Microsoft Office, 2013). The distribution of PBDEs in the different matrices was assessed using Shapiro–Wilk statistic. As the majority of distributions were not normal, non-parametric Spearman's ranking correlation coefficients were determined. The criteria of $\alpha = 0.05$ for statistical significance was used. A one sample *t*-test was used to compare PBDE intake of omnivorous participants as determined by duplicate diet collection and similar data collected by Harrad et al. (2004) to investigate any temporal trend in dietary exposure. Statistical analyses were mostly descriptive and correlations do not have sufficient sample numbers to be robust. Details of further statistical analyses of room survey data are presented in the Supplementary Information. Where measurements were below limits of detection (LOD) values of LOD × 0.5 have been assumed (median bound). $\sum BDEs_{3-7}$ was calculated as the sum of all BDE

congeners measured except for BDE-209.

2.8. Human health risk characterisation

Potential health risks were calculated from the sum of dust and dietary intake of PBDEs using the margin of exposure (MOE) approach as applied by the European Food Safety Authority (EFSA) for dietary exposure health risk assessment. The MOE is the ratio of the dose at which a small but measureable adverse effect has been reported versus the level of exposure of the population under current consideration. The EFSA Panel on Contaminants in the food chain (EFSA, 2011) identified effects on neurodevelopment as the critical endpoint using $BMDL_{10}$ for neurobehavioural effects in mice induced during a relevant period for brain development. Chronic human intakes, associated with body burdens at the $BMDL_{10}$ for BDEs-47, -99, -153 and -209, were estimated to be 172, 4.2, 9.6 and 1,700,000 ng kg^{-1} bw day^{-1} respectively. For PBDEs, EFSA consider that an MOE ratio above 2.5 indicates that a health concern is unlikely, with risk decreasing as the MOE increases (EFSA, 2011). It should be noted that although human intakes of concern are presented as daily doses these represent chronic intake and as such would be better represented as weekly or monthly intakes as daily intakes can be exceeded on occasion without concern as long as other days have lower exposures.

3. Results and discussion

Our cohort consisted of 10 male-female cohabiting couples living in northeast England in 2011/12. All participants completed full sample and data set collection. Participants were recruited from as wide a pool of socio-economic class, occupation, diet and location as possible, however, the small number of participants and the focus on breastfeeding mothers means that results are not representative of all UK residents' exposures. The benefit of the small cohort was that detailed information could be collected for each individual allowing the investigation to include almost all contributing factors in PBDE exposure known at the time. Further details of occupations, diets, parity, breastfeeding and other lifestyle and anthropometric factors are presented in Supplementary Information. Previously published serum, breastmilk, and duplicate diet concentrations (Bramwell et al., 2014; 2016) have been further examined in this investigation, along with new matched dust concentrations, diet and dust intake estimations and exposure and food frequency questionnaire, seven day food and activity diary and room survey information in order to provide as complete a picture of participants' PBDE exposures as possible.

3.1. Dust PBDE concentrations

Dust samples were collected from 40 micro-environments frequently used by the study participants. Main living areas ($n = 10$), bedrooms ($n = 12$) and home offices ($n = 2$) were sampled. Workplaces were sampled if access was granted by employers ($n = 8$). None of the domestic samples were from open plan homes. Four of the workplace samples were from open plan indoor spaces. Vehicles were sampled if participants regularly spent more than 5 h each week in them ($n = 8$). We measured PBDEs in dust from all of the microenvironments sampled. Individual concentrations for all PBDEs in each dust sample are presented in Supplementary Information Table SI 1–4 and summaries of the dust concentrations in different rooms are presented in Table 1. Median dust $\sum BDEs_{3-7}$ concentrations were highest in vehicles (179 ng g^{-1}) followed by living rooms, bedrooms then workplaces (137, 102 and 84 ng g^{-1} respectively). Median BDE-209 concentrations in dust were also highest in vehicles (19,000 ng g^{-1}) then bedrooms, living rooms and workplaces (3,530, 2,960, and 2300 ng g^{-1} respectively). The highest concentration of $\sum BDEs_{3-7}$ was measured in a bedroom (7,320 ng g^{-1} dust), the highest BDE-183 in the rear of a work van (367 ng g^{-1}) and the highest BDE-209 in a car (137,000 ng g^{-1}). Summaries of dust PBDE concentrations in the different microenvironments are compared with previous UK and international data in Table 2. Measurements in this study were in keeping with previously published UK data (Harrad et al., 2008a,b; Pless-Mulloli et al., 2006; Sjödin et al., 2008) and in agreement with the theory that BDE-209 usage was greater in the UK (Fromme et al., 2016; Harrad, 2015). Results were directly comparable to studies by Harrad et al. (2008a,b) as we used the same sampling protocol, sampling equipment and laboratory techniques.

We compared room survey information such as counts and age of soft furnishings and electronics and room cleaning frequencies with the concentrations of PBDEs in each room. Details from individual room surveys are provided in Supplementary Information Table SI5. We did not find that simple counts of soft furnishings or electronics were good predictors of high or low PBDE loading. The clearest association between room contents and PBDE concentrations in dust were for BDE-209 if the room contained a carpet or rugs over 20 years of age (see Supplementary Information Fig. 2). Counts of large PUF items over 20 years old or office chairs from the USA (adhering to Californian state fire retardancy regulations TB117) correlated significantly with concentrations of Penta mix BDEs only, BDE-47 ($r = 0.37$, $p = 0.036$), −99 ($r = 0.35$, $p = 0.047$) and $\sum BDE_{3-7}$ ($r = 0.37$, $p = 0.039$). Higher dusting frequency demonstrated the greatest correlation with lower dust PBDE concentrations, with BDEs-47, −99, −153, −154 and −209 all with correlation significant at the 0.01 level and BDE-100 with correlation significant at the 0.05 level. Table SI 6 in the Supplementary Information contains further correlation data. Discussion of apparent differences between repeat sampling weeks' dust data is provided as Supplementary Information.

We found that concentrations of ∑Penta product BDEs in the bedroom were significantly correlated with those in all other environments measured; living rooms ($r = 0.43$, $p = 0.05$), workplaces ($r = 0.71$, $p = 0.05$) and vehicles ($r = 0.90$, $p = 0.02$). Concentrations of ∑Penta product BDEs in living room dusts correlated strongly with those in workplaces ($r = 0.90$, $p = 0.01$) but not vehicles ($r = 0.30$, $p = 0.60$). A larger data set may have revealed alternative findings, particularly for workplaces and vehicles. We suggest that dust particles may briefly adhere to and then be shaken from skin, hair, clothing and footwear causing distribution among key environments used by participants. Further correlation data is provided in Supplementary Information Table SI13.

3.2. Intake of PBDEs via dust

The ranges of average (20 mg dust ingested d^{-1}) and high (50 mg dust ingested d^{-1}) PBDE intakes via dust for our study participants was 13.8–1,010 and 35–2,520 pg kg^{-1} bw day^{-1} for $\sum BDEs_{3-7}$, with 281 to 15,900 and 702 to 39,600 pg kg^{-1} bw day^{-1} for BDE-209 via dust. Our $\sum BDEs_{3-7}$ intake estimates were similar to previous UK and German $\sum BDEs_{3-7}$ estimates (Fromme et al., 2009; Harrad et al., 2008a) and an order of magnitude lower than those in the USA (Harrad et al., 2008b). In contrast, our BDE-209 intakes from dust were similar to those of the USA (Harrad et al., 2008b) and an order of magnitude higher than Belgian and German estimates (Fromme et al., 2009; Roosens et al., 2009) (see Supplementary Information Table 6). The wide range of intakes reflected the diverse PBDE loadings measured in microenvironment dusts. For this cohort, the influence of specific items in specific microenvironments could be reasonably speculated on a case

Table 1
Summary of PBDE concentrations in different room dusts and matrices for this study.

PBDEs	Matrix	Detection rate (%)	Median	Mean	Range	P90
BDE-47	Bedroom dusts (n = 12) (ng/g dust)	100	26.7	255	4.93–1930	164
	Living room dusts (n = 11[b]) (ng/g dust)	100	34.3	45.18	5.2–384	47.7
	Workplace dusts (n = 10) (ng/g dust)	100	16.1	99.5	2.10–417	255
	Vehicles (n = 8) (ng/g dust)	100	23	38.5	15.8–105	74.1
	24 h duplicate diet (n = 24) (ng/g lw)	100	0.1	0.18	0.04–0.86	0.31
	Serum (n = 24) (ng/g lw)	63	1.21	1.28	0.36[a]–3.35	2.13
	Milk (n = 6) (ng/g lw)	100	1.92	3.75	0.32–13.1	8.31
BDE-99	Bedroom dusts (n = 12) (ng/g dust)	100	28.6	506	6.87–3940	324
	Living room dusts (n = 11[b]) (ng/g dust)	100	48.9	53.4	5.90–389	59.8
	Workplace dusts (n = 10) (ng/g dust)	100	24.1	192	5.8–776	562
	Vehicles (n = 8) (ng/g dust)	100	43.5	87.9	18.3–344	185
	24 h duplicate diet (n = 24) (ng/g lw)	100	0.1	0.14	0.03–0.44	0.3
	Serum (n = 24) (ng/g lw)	75	0.79	1.22	0.35[a] –5.61	2.54
	Milk (n = 6) (ng/g lw)	100	0.88	1.18	0.12–3.74	2.39
BDE-153	Bedroom dusts (n = 12) (ng/g dust)	100	14.18	50.3	3.51–311	46.9
	Living room dusts (n = 11[b]) (ng/g dust)	92	7.88	30.9	0.40–118	67
	Workplace dusts (n = 10) (ng/g dust)	100	8.86	27.1	0.80–93.0	72
	Vehicles (n = 8) (ng/g dust)	100	16.3	27.8	1.44–117	50.9
	24 h duplicate diet (n = 24) (ng/g lw)	88	0.02	0.03	0.01–0.10	0.05
	Serum (n = 24) (ng/g lw)	100	0.37	0.67	0.12–4.05	1.03
	Milk (n = 6) (ng/g lw)	100	1.01	1.1	0.70–1.68	1.53
BDE-183	Bedroom dusts (n = 12) (ng/g dust)	100	5.36	8.2	1.98–31.6	9.05
	Living room dusts (n = 11[b]) (ng/g dust)	100	10.2	11.3	0.90–33.5	16.4
	Workplace dusts (n = 10) (ng/g dust)	100	7.41	51.4	0.90–367	36.3
	Vehicles (n = 8) (ng/g dust)	100	6.55	52.34	2.11–367	124
	24 h duplicate diet (n = 24) (ng/g lw)	96	0.01	0.02	0.003–0.08	0.03
	Serum (n = 24) (ng/g lw)	67	0.05	0.09	0.02[a]–0.33	0.18
	Milk (n = 6) (ng/g lw)	100	0.05	0.07	0.02–0.23	0.15
BDE-209	Bedroom dusts (n = 12) (ng/g dust)	100	3530	17,300	33.0–107,000	19,500
	Living room dusts (n = 11[b]) (ng/g dust)	100	2960	22,000	126-106,000	55,500
	Workplace dusts (n = 10) (ng/g dust)	100	2360	9590	728-40,000	16,200
	Vehicles (n = 8) (ng/g dust)	100	19,000	41,000	315-137,000	120,000
	24 h duplicate diet (n = 24) (ng/g lw)	63	0.73	0.85	<0.001–3.13	1.52
	Serum (n = 24) (ng/g lw)	17	1.73	2.81	<1.13–19.8	4.62
	Milk (n = 6) (ng/g lw)	83	0.52	0.58	<0.19–1.04	1.02
∑tri-hepta BDE	Bedroom dusts (n = 12) (ng/g dust)	100	102	1040	28.4–7325	736
	Living room dusts (n = 11[b]) (ng/g dust)	100	137	189	25.5–1060	257
	Workplace dusts (n = 10) (ng/g dust)	100	83.6	415	16.6–1500	1040
	Vehicles (n = 8) (ng/g dust)	100	179	251	88.1–677	504
	24 h duplicate diet (n = 24) (ng/g lw)	100	0.3	0.5	0.10–1.40	1.06
	Serum (n = 24) (ng/g lw)	100	3.07	4.14	0.78–12.6	8.07
	Milk (n = 6) (ng/g lw)	100	4.8	7.47	1.33–21.0	14.7

Notes:
[a] Limits of detection varied between batches therefore some measurable values were lower than some LODs.
[b] The living area of Couple 6 yielded insufficient sample for analysis.

by case basis. However, although we expected our participant with occupational PUF and furnishing fabric exposure to have a raised PBDE body burden, their fastidious cleaning habits appear to have reduced their exposure.

The greatest proportion of the estimated dust intake for $\sum BDEs_{3-7}$, BDE-183 and BDE-209 took place in the bedroom (means 43%, 38% and 33% respectively) due to the greater amount of time spent in bedrooms. Workplaces and living rooms were the second most important microenvironments for $\sum BDEs_{3-7}$ exposure (mean 19%, 13%) and BDE-183 (20%, 21%). Vehicles were the second most important microenvironment for BDE-209 intake (20%). The relative proportions of PBDE intakes in different microenvironments for individual participants is illustrated in Fig. 1. Our finding that the greater proportion of exposure to all congeners occurs in the bedroom is in keeping with our finding of an association between bedroom dust and serum concentrations of the PBDE congeners found in the commercial Penta-BDE products (BDE-47, −99, −100, −153) ($r = 0.42$, $p = 0.04$), an association that has also been reported elsewhere (Ali et al., 2014; Coakley et al., 2013; Watkins et al., 2012).

3.3. Relationships between PBDE in dust and body burdens

We compared PBDE concentrations in dust in the different indoor environments with their matched PBDE body burdens. Significant associations were noted between Penta-mix BDEs in bedroom dust and serum ($r = 0.45$, $p = 0.04$). BDE-153 in bedroom dust was significantly associated with BDEs-47 ($r = 0.45$, $p = 0.03$), −99 ($r = 0.45$, $p = 0.03$), −209 ($r = 0.41$, $p = 0.05$) and $\sum BDEs_{3-7}$ ($r = 0.45$, $p = 0.03$) in serum. BDE-153 in serum was associated but not significantly with BDEs-153 (0.39, 0.06) and $\sum BDEs_{3-7}$ (0.39, 0.06) in bedroom dust. BDE-47 was associated but not significantly in living room dust and breast milk (0.77, 0.07). BDE-209 was significantly correlated in serum and workplace dusts (0.72, 0.02) however this was strongly influenced by one data point. Also correlated but not significantly in workplace dusts were BDEs-47 (0.57, 0.07) and −99 (0.53, 0.09). Table SI 7 in Supplementary Information provides further dust and body burden correlation data. No significant correlations were found between vehicle dust and serum despite vehicles having the highest PBDE concentrations in their dust, possibly due to participants spending less time in their

Table 2
Summary of concentrations of PBDEs in UK indoor dusts with international data for comparison.

Reference	Sample date	BDE-47 (ng/g)	BDE-99 (ng/g)	BDE-153 (ng/g)	BDE-183 (ng/g)	BDE-209 (ng/g)	Comments
This study	2011/12	27 (5–1930) 273	38 (7–3940) 405	14 (4–311) 78	6 (2–32) 26	3530 (33–107,000) 19,500	Median (range) P90, bedroom dust (n = 11 + 2 rpt samples)
This study	2011/12	34 (5–384) 59	49 (6–389) 59	18 (1–118) 65	10 (2–33)13	2960 (126–106,000) 42,730	Median (range) P90, main living area (n = 10 + 1 rpt sample)
This study	2011/12	299 (12–417) 393	665 (24–776) 754	84 (4–93) 91	7 (5–17) 15	7740 (2480–40,000) 33,500	Median (range) P90, home offices (n = 2, +1 rpt sample)
This study	2011	13 (2–61) 50	20 (6–63) 53	5 (1–18) 16	6 (2–18) 16	1030 (728–4950) 3480	Median (range) P90, workplaces, n = 7
This study	2011	23 (16–105) 76	48 (18–344) 231	15 (1–117) 70	7 (2–20) 14	13,300 (315–137,000) 83,900	Median (range) P90, car cabin, n = 6
This study	2011	16	18	18	367	17,100	Van rear storage, n = 1
This study	2011	61	82	21	3	111,000	Train, n = 1
UK							
Harrad et al. (2008a)	2006/7	15 (1.2–58)	36 (2.8–180)	14 (BDL-110)	71 (BDL-550)	260,000 (BDL-2,200,000)	Average (range), homes, n = 30
Sjödin et al. (2008)	2007	22 (7–180)	28 (10–300)	5 (<2–53)	5 (<3–18)	10,000 (910–54,000)	Median (range), homes, n = 10
Pless-Mulloli et al. (2006)	2005	(9–62)	(8–85)	(1–10)	(1–20)	(1401–54,900)	(Range), homes, n = 7
Santillo et al. (2003)	2002	25 (10–1980)	44 (18–2100)	23 (<0.1–170)	9.5 (<0.1–87)	7100 (3800–19,900)	Median (range), homes, n = 10
Harrad et al. (2008a; b)	2006/7	67 (2.6–380)	120 (4.2–490)	16 (BDL-99)	11 (BDL-24)	30,000 (620–280,000)	Average (range), offices, n = 18
Harrad et al. (2010)	2007/8	32 (1.6–120)	54 (1.1–270)	28 (<2–310)	5.1 (<2–48)	8500 (49–88,000)	Average (range), classrooms, n = 43
Harrad and Abdallah (2011)	2009	501 (28–3600)	619 (45–4200)	65 (BDL-400)	11 (<1–59)	265,000 (28,000 –620,000)	Average (range), car cabins, n = 14
Harrad et al. (2008a; b)	2006/7	720 (19–7500)	990 (23–8000)	150 (BDL-1500)	19 (BDL-67)	410,000 (12,000 –2,600,000)	Average (range), cars, n = 20
Harrad and Abdallah (2011)	2009	28 (5.0–71)	47 (14–100)	11 (BDL-41)	2.4 (<1–11)	3744 (180–11,000)	Average (range), car boots, n = 14
Europe							
Korcz et al. (2017)	2012/13	21 (<2–950)	33 (<2–1370)	2.6 (<2–24)	–	5580 (36–6000)	Average (range), homes, n = 129, Poland
Newton et al. (2015)	2012	16 (<0.4–150)	32 (<4–200)	<12 (<12–17)	–	90 (<31–130)	Geometric mean (range) homes, n = 27, Sweden
Civan and Kara (2016)	2015/16	10 (1–260)	6 (1–254)	14 (1–304)	21 (3–404)	138 (13–1740)	Median (range), homes, n = 40, Turkey
Cequier et al. (2014)	2012	126 (1510)	171 (2610)	26.0 (254)	3.22 (267)	325 (204,000)	Median (maximum), living rooms, n = 48, Norway
Cequier et al. (2014)	2012	46.9 (199)	42.4 (92.8)	8.93 (37.2)	5.80 (15.9)	507 (5270)	Median (maximum), classrooms, n = 6, Norway
Fromme et al. (2009)	2005	9 (2–255)	13 (2–390)	3 (0.3–41)	4 (0.3–60)	312 (30–1460)	Median (range), homes, n = 34, Germany
Global							
Kim et al. (2016)	2009	5 (1–30)	11 (2–38)	1.5 (0.5–8)	1.3 (0.4–48)	829 (66–4,44)	Median (range), homes, n = 15, Korea
Stapleton et al. (2014)	2012	452 (55–24,700)	741 (8.0–36,200)	40.6 (3400)	1.0 (<0.06–4.5)	1720 (441–76,100)	Geometric mean (range) homes, n = 30, USA
Batterman et al. (2009)	2006/7	6400 (46,00)	4600 (79,000)	230 (790)	840 (7600)	11,000 (66,000)	Average (maximum) homes, n = 12, USA
Sjödin et al. (2008)	2007	60 (20–1400)	100 (26–3400)	13 (5–410)	14 (<6–99)	730 (23–13,000)	Median (range), homes, n = 10, Australia
Sjödin et al. (2008)	2007	430 (230–3000)	880 (70–3700)	140 (5–650)	70 (<4-4000)	2,00 (520–29,000)	Median (range), homes, n = 10, USA
Batterman et al. (2009)	2006/7	5000 (30,000)	9300 (63,000)	1000 (7200)	27,000 (31,000)	15,000,000 (210,000,000)	Average (maximum) cars, n = 12, USA

cars than in other environments measured. The associations between bedroom dust and serum might be expected due to participants spending the greatest proportion of their day in this room, similarly for associations with workplace dust and serum.

3.4. Dietary intake of PBDEs

We estimated participants' PBDE intake from diet using three different methods, (i) a 24 h duplicate diet sample collected the day before taking serum and milk samples, (ii) a seven day food diary completed the seven days prior to serum and milk sampling and (iii) a food frequency questionnaire (FFQ) to represent longer term eating habits. Concentrations of PBDEs in the 24 h duplicate diet samples summarised in Table 1. $BDEs_{3-7}$ were measurable in all of the duplicate diet samples and BDE-209 in 79% of them. 24 h duplicate diet PBDE concentrations were converted to daily dietary intake estimates which ranged from 82 to 1320 pg kg^{-1} bw for $\sum BDEs_{3-7}$ and <0.8–1860 pg kg^{-1} bw for BDE-209. BDE-209 made up a median of 73% of the total PBDE exposure from diet. Estimates of individuals' PBDE intake via diet are provided in Supplementary Information Table SI 11. The mean intake estimates of BDEs-47, –99, –100, –153 and –154 for the omnivores in this study were significantly lower than those measured by Harrad et al. (2004) for duplicate diet samples collected in the West Midlands

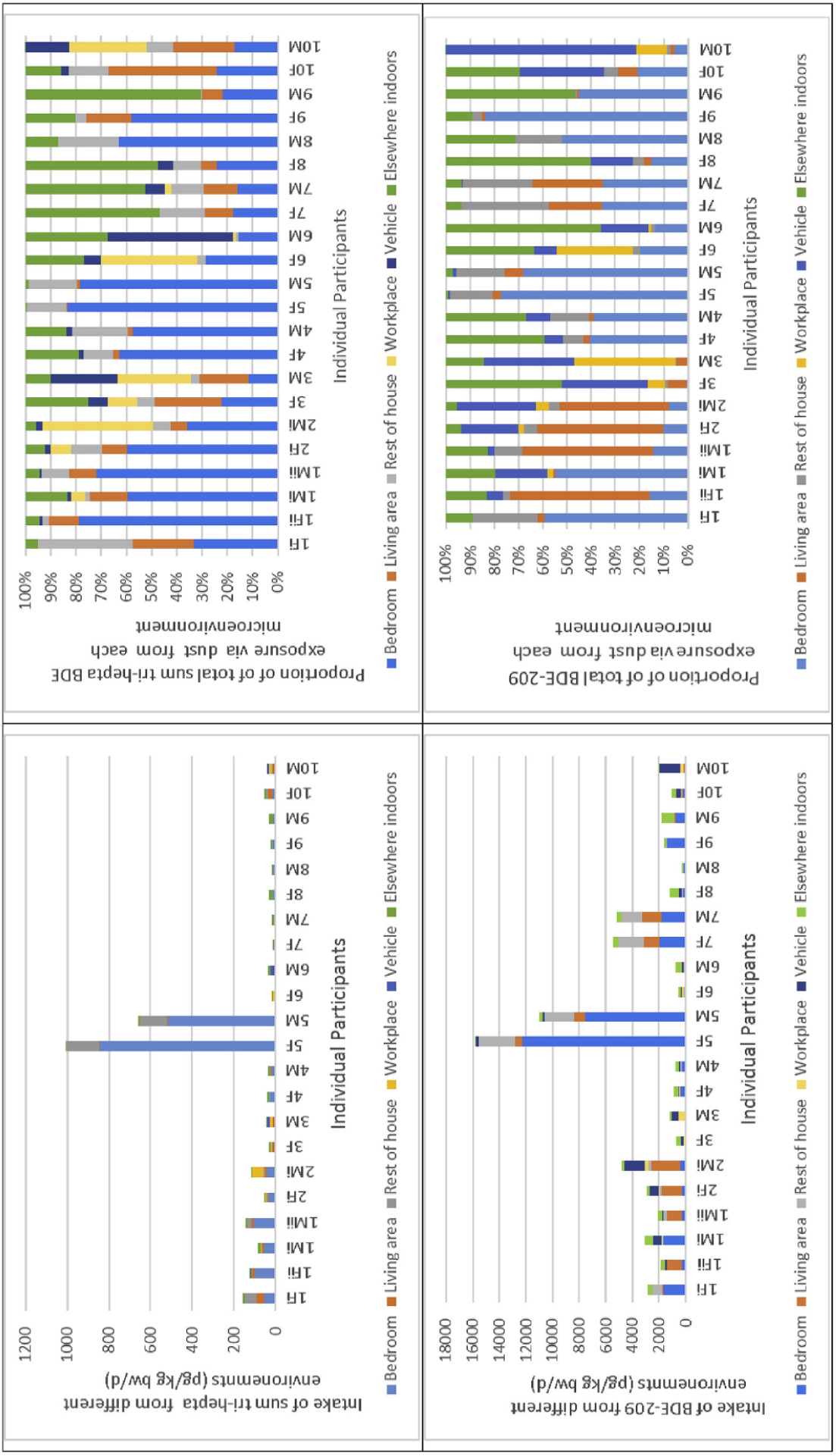

Fig. 1. Individuals' proportional exposure to PBDEs via dust in different environments, calculated from dust concentrations and seven day activity diary data.

of the UK in 2002 ($p = 0.01$). The 2002 lower bound mean intakes were within the maximum intakes estimated by this study for BDEs −47, −100, −153 and −154 and upper bound intakes for BDEs −47, −100, and −154. These findings indicate a reduction in dietary exposure during the 10 years between the two studies, with the greatest reductions being for BDE-99 then BDE-153.

Meat, fish and dairy portion consumption estimates compared well between the FFQ and seven day food diaries. Meat portions consumed per week ranged from none to 14 or 15 (FFQ and diary respectively), with median 6.3 or 8 portions. Fish and seafood portions consumed per week ranged from none to 3.5 (maximum for both FFQ and diary), with median 1.8 or 2 portions. Dairy portions consumed per week ranged from none to 25 or 18 (FFQ and diary respectively), with median 8.0 or 8.5 portions. A summary of selected information from the FFQ, diary and 24 h duplicate diet is presented in Table 3.

3.5. Relationships between PBDE in diet, serum and breastmilk

We compared PBDE body burdens with concentrations in the duplicate diet finding a significant association for $\sum BDEs_{3-7}$ in both ($r = 0.41$, $p = 0.05$). Serum samples were collected from fasted participants in order for the serum sample to represent the participants' background PBDE body burden without influence from recently consumed food. Breastmilk samples were not necessarily collected in a fasted state. The complex relationship between historic PBDE deposits in adipose tissue, recent diet, serum and breastmilk is beyond the scope of this paper. We found limited correlation between congeners in serum and breastmilk (see Supplementary Information Table SI 8), possibly the result of transfer of PBDEs from serum to milk varying between different congeners. Mean serum/milk ratios generally increased with molecular size and hydrophobicity, e.g. 1.3, 3.1 and 6.0 for BDEs-47, −99 and −209. This pattern was in keeping with findings of a 2012 review of PBDE in matched serum and breastmilk samples (Mannetje et al., 2012). BDE-153 in the body appears to follow a different pattern with a serum/milk ratio of 0.4, i.e. more in milk than serum.

We found that the number of meat portions consumed in the week prior to sampling had significant positive correlations with BDEs-99 ($r = 0.46$, $p = 0.01$) −153 ($r = 0.44$, $p = 0.03$) and $\sum BDEs_{3-7}$ ($r = 0.43$, $p = 0.04$) in serum. Further correlation data between dietary information is provided in Supplementary Information Table SI 9. The UK FSA 2006 TDS found meat products (followed by fish) to contribute most to the PBDE intake of the general UK population (EFSA, 2011; FSA, 2006). For participants in this study, meat portions consumed exceeded fish portions. Our earlier review of associations between PBDE body burden, dust and diet (Bramwell et al., 2016) also found eating meat to be the most frequently reported association (eating dairy and fish were next). Similarly, a nationwide study in the USA found vegetarians to have 23% lower, and heavy red meat consumers to have 18% higher total PBDEs in serum than omnivores (Fraser et al., 2009).

3.6. Anthropometric and questionnaire covariates of PBDE body burden

As well as participants' height, weight and body fat mass measurements, information on travel habits, hand to mouth behaviours, parity, numbers of household members, hobbies and occupations was also collected to look for indicators of higher serum and breast milk PBDE concentrations. These associations are presented in Supplementary Information Table SI 10. We found serum BDE-153 concentrations to be significantly associated with sex ($r = -0.60$, $p = 0.01$), percentage of body fat mass ($r = -0.49$, $p = 0.02$), parity in women ($r = -0.57$, $p = 0.05$) and working with electronics ($r = 0.59$, $p = 0.01$). Males generally had higher BDE-153 in serum than females, in keeping with the findings of a recent Swedish study of 170 adults (Bjermo et al., 2017) and a nationwide study in the USA that found males generally had higher BDE_{3-7} body burdens (Fraser et al., 2009). We hypothesise there may be two factors influencing the higher serum concentrations of males in this study, (i) men generally had lower BMI values; seven of the females had recently been pregnant which would increase their BMI and (ii) 9 of the 10 female participants in the study had undergone some depuration effect during pregnancy and breast feeding which their male partners had not. In a study of the breastmilk of 83 women at three and 12 months postpartum, BDE-153 showed a significant increase over time (Daniels et al., 2010) suggesting that BDE-153 present in adipose fat compartments from historic exposures may be mobilised during the nursing period. Storage of BDE-153 in fat compartments in the body has been suggested as the reason for dilution in the serum of people with higher BMI (Cequier et al., 2015; Fraser et al., 2009). Why these

Table 3
Summary of selected information from the food frequency questionnaire, food diary, activity diary and exposure questionnaire.

Questionnaire & Survey Information		min	max	median	avg	P90
FFQ	Meat portions consumed per week	0	15	6.3	6.3	10.9
Food Diary	Meat portions consumed per week	0	14	8	8.1	11.3
24 h DD	Meat portions consumed in 24 h	0	3	1	1.2	2
FFQ	Fish & seafood portions consumed per week	0	3.5	1.8	1.8	3.5
Food Diary	Fish & seafood portions consumed per week	0	3.5	2	1.9	3.5
24 h DD	Fish & seafood portions consumed in 24 h	0	1	0	0.2	1
FFQ	Dairy portions consumed per week	0	25	8	8.8	12.6
Food Diary	Dairy portions consumed per week	2	18	8.5	9.2	14.5
24 h DD	Dairy portions consumed in 24 h	0	5	2	2.3	5
Activity Diary	On computer or gaming (hrs:mins)	00:00	09:04	00:28	01:50	05:28
	Watching TV (hrs:mins)	00:00	04:00	01:36	01:38	02:46
	Main house bedroom (hrs:mins)	06:21	11:10	09:08	09:07	10:50
	Proportion of day in bedroom (%)	26	47	38	38	45
	Main house living area (hrs:mins)	00:17	09:23	03:57	04:20	07:14
	Proportion of day in living area (%)	1	39	16	18	30
	Workplace (hrs:mins)	01:05	09:43	03:11	04:13	06:28
	Proportion of day in workplace (%)	0	41	0	7	22
	Time in main vehicle (hrs:mins)	00:17	05:34	00:57	01:16	02:32
	Proportion of day in vehicle (%)	0	23	3	4	10
Room survey info	Number of electronic items per room	1	39	6	8	14

findings for BDE-153 are not consistent with findings for other congeners is not clear but it may be linked to its longer human half-life (Geyer et al., 2004).

3.7. Was diet or dust the major source of PBDE exposure for this cohort?

Diet was the major source of $\sum BDEs_{3-7}$ for this cohort making up a median of 85% of the total intake when using duplicate diet data with the average dust ingestion estimate of 20 mg d^{-1}. This was a somewhat lower proportion than comparable previous studies estimates of 95% (UK), 96% (Belgium) and 97%, (Germany) (Abdallah and Harrad, 2014; Fromme et al., 2009; Roosens et al., 2009) due to our higher median $\sum BDEs_{3-7}$ dust concentration and the notably higher concentration of $\sum BDEs_{3-7}$ in the German duplicate diets (see Table SI 6). We did not include estimates of intake of PBDEs from indoor air in our totals. Previous studies have found PBDE intake from air to constitute <1% of total PBDE intake (Fromme et al., 2009) and a maximum of 2% (Abdallah and Harrad, 2014).

Considering only a cohort's average intake hides the substantial variation between individuals and their exposure sources - something this study has been able to demonstrate clearly (see Fig. 2 and Supplementary Information Table SI 6). An individual's total PBDE intake is a combination of dust concentrations in different environments, time spent in them and dietary habits. For example, the proportion of $\sum BDEs_{3-7}$ BDE intake provided by dust for an average dust intake rate had a median 4% but ranged between 0.7% (8M) and 32% (5F). Both these participants lived rurally, the former on a smallholding, the other on a farm. 8M spent the most time outdoors (almost 9 h each day), had a low Penta-BDE loading in their bedroom dust and, despite a generally home-grown and organic diet, a duplicate diet intake in the 3rd quartile. 5F's relatively high dust intake (32% using average dust intake and 54% using high dust intake rates) was due to having the room (bedroom) with the highest $\sum BDEs_{3-7}$ concentrations measured in the study. Although 5F consumed a vegetarian diet their dietary $\sum BDEs_{3-7}$ intake was in the top quartile.

Dust was the greatest source of BDE-209 for our entire cohort, with median intakes making up 75% and 88% of the total BDE-209 intake for average and high dust intake rates respectively, lower than previous UK estimates of 94% and 99% (Abdallah and Harrad, 2014; Harrad, 2010) possibly due to declining use of Deca-BDE product and differences between cohorts in the different studies. Individual participants' proportion of total BDE-209 intake provided by dust for average dust intake rate ranged from 14% (8M) to 100% (1Fii and 1Mii). Participant 10M had a significantly greater BDE-209 concentration than their partner possibly a reflection of the relatively high amount of time spent in their vehicle (23% of their time) and BDE-209 concentration in their car (30,338 ng/g).

We found the range of individuals' intakes of $\sum BDEs_{3-7}$ from dust to be five times greater than their intakes from diet. The highest total intake (using average dust intake scenario) was 16 times greater than the lowest reported intake. Our data agrees with previous hypotheses that the wide range in PBDE concentrations in room dusts (compared with the range seen in diets) may be the reason some individuals have significantly higher internal dose (Harrad et al., 2008b; Petreas et al., 2003; Thomas et al., 2006; Wu et al., 2007). Dust generation, dust ingestion rates, and cleaning frequencies (both microenvironments and hand washing) may also be influential.

Our study corroborates previous studies findings that average PBDE intakes in the UK are broadly similar to those in mainland Europe, where meat is the major source of Penta-BDEs for the average person but dust is the major source of BDE-209 (Bramwell et al., 2016; Harrad et al., 2008b). For infants, the average contribution to total intakes from diet were >90% for $\sum BDEs_{3-7}$ and 69% for BDE-209. At the high dust ingestion rate this decreased to 35–50% for $\sum BDEs_{3-7}$ and 88% for BDE-209. These figures indicate similar proportional intake for infants from diet to our adults, although with considerably higher amounts ingested per kg body weight (see Table 3).

3.8. Study limitations

This study involved a relatively small cohort of 20 individuals (10 UK couples). The study philosophy concentrated more on the details and habits of the volunteers in order to understand their individual exposures. The volume of usage of PBDE mixtures such as PentaBDE, the timelines of product introduction and restriction, either voluntary or regulation enforced, and the type of usage, are all variables in general population exposure. For example, a far greater volume of the PentaBDE mixture was used in the USA and Canada compared to Europe and this is reflected in the relatively higher concentrations of related congeners measured in serum, and in house dust levels from North America. Also, where we found diet to be the most important exposure pathway for Penta mix BDEs, studies such as that by Lorber (2008) have shown that dust is a major pathway for PentaBDE in North American populations. When personal details and habits are considered, the exposure assessment is even more unique. Thus, the finding of this study are not intended to be representative of the UK as a whole, or even less, other regions of the world.

3.9. Risk characterisation

The most relevant congener from a health risk perspective is BDE-99 but there is no agreement on a safe intake. The US-EPA suggests a reference dose 100 ng/kg bw/day (US-EPA, 2006) whereas the more recent EFSA suggested health reference value is 4.2 ng/kg bw/day with an MOE of 2.5 (EFSA, 2011). We investigated potential health risk from our estimated PBDE intakes by comparing them with both these reference values (see Table 4 and Table SI12). The combined uncertainties from household types, sampling and measurement is likely to be quite high and should be borne in mind. No health concerns are expected from the PBDE intakes estimated in this study for adults as all had MOEs over 2.5 (EFSA, 2011). The lowest adult MOEs were 2.8 and 3.7 for BDE-99 using a high dust intake rate for household 5 with the high BDE_{3-7} measurements in their bedroom. Accordingly, estimated infant daily exposures to BDE-99 for the same home have MOEs below those recommended by EFSA for chronic exposure. Using average dietary intake data from the 2012 UK TDS with dust exposure data from this study with average dust intake rates we found the lowest MOE estimation to be 2.3 which is similar to the EFSA recommended MOE of 2.5 deemed to indicate a potential health risk. Using high dust intake rates with dust data for this study and 97.5th percentile (P97.5) dietary intake estimates from the 2012 UK TDS this MOE dropped to 0.7 and two additional homes indicated high infant intake MOEs between 2.5 and 3. All other adult and infant MOEs using EFSA reference values and all MOEs using US EPA values were comfortably above the recommended MOE. Follow-up measurement of the PBDE body burdens for infants of parents participating in this study could help describe associations with raised intake estimations.

4. Conclusions

This detailed study is the first anywhere to document concentrations of PBDEs, including BDE-209, in samples of indoor dust and

Fig. 2. Comparison of individual participants' ∑tri-hepta BDE and BDE-209 intakes via dust and diet using average (20 mg day^{-1}) dust intakes and 24 h duplicate diet data (pg kg^{-1} bw d^{-1}).

Table 4
Summary of adult (using average and high dust intake scenarios and duplicate diet data from this study) and infant (using average and high dust intake scenarios from this study and average and high dietary intake estimates from the UK FSA TDS, 2011) PBDE intakes and associated Margins of Exposure (MOEs) with EFSA health reference values.

Total PBDE Intake (pg/kg bw/day)	BDE-47	BDE-99	BDE-153	BDE-209	BDE-47	BDE-99	BDE-153	BDE-209	BDE-47	BDE-99	BDE-153	BDE-209	BDE-47	BDE-99	BDE-153	BDE-209
	Sum adult mean dust intake + DD				Sum adult high dust intake + DD				Sum infant average dust intake + average TDS				Sum infant high dust intake + P97.5 TDS			
Mean	171	155	29	3750	219	240	43	8380	683	610	121	16,300	1510	1430	283	44,500
Min	30	30	8	1170	39	40	12	2240	610	480	100	9210	1220	910	200	16,200
Median	89	93	23	2210	106	103	34	4730	627	500	112	13,500	1290	990	249	33,300
Max	822	685	86	17,000	876	1493	151	41,000	1270	1830	210	49,000	3860	6290	639	174,000
EFSA Chronic intake value (ng/kg bw/day) (2011)	172	4.2	9.6	1,700,000	172	4.2	9.6	1,700,000	172	4.2	9.6	1,700,000	172	4.2	9.6	1,700,000
	Adult mean MOEs				Adult high MOEs				Infant mean MOEs				Infant high MOEs			
Mean	2290	55	512	745,000	1890	45	354	380,000	258	7.57	80.7	118,000	121	3.67	35.6	49,500
Min	209	6	112	100,000	196	3	63	41,700	135	2.3	45.8	34,800	45	0.67	15	9730
Median	1940	45	417	769,000	1620	41	292	360,000	274	8.38	84.2	123,000	133	4.22	37.5	49,300
Max	5660	138	1210	1,460,000	4460	105	808	760,000	279	8.6	91.7	172,000	138	4.45	43.9	89,400

Notes DD = duplicate diet, UK FSA TDS = UK Food Standards Agency's total diet study, P97.5 = 97.5 percentile.

diet with matched human serum and breast milk concentrations. Our findings confirmed that both diet and dust make a contribution to PBDE body burdens and provide new evidence of a wide range in their relative contributions between individuals. Diet appeared to be the primary source of intake of $BDE_{3–7}$ congeners for the majority of this cohort, and meat consumption demonstrated the strongest significant positive association between diet type and serum $BDEs_{3–7}$ concentrations. Dust was the cohort's primary source of BDE-209. Rooms containing a carpet or rugs over 20 years old had higher BDE-209 concentrations in their dust. Rooms that were dusted more frequently had less BDE-209, as well as less Penta mix PBDE congeners. Rooms containing sofas or armchairs over 20 years old had higher concentrations of commercial Penta mix PBDE congeners. BDE-209 concentrations in room dusts did not widely correlate with BDE-209 body burdens, possibly due to the congener's relatively large molecular size and low bioaccessibility. Correlations between $BDE_{3–7}$ congeners in serum and indoor dust were strongest in bedrooms in keeping with the greater proportion of time spent there. Being male and having a lower body fat mass were indicators of higher serum BDE-153 for this cohort. BDE-99 was the congener demonstrating the lowest MOE (and therefore the greatest health risk) and although we found a reduction in dietary exposure to this and other Penta-mix PBDEs since 2002, reducing dietary exposure would still have the greatest effect in reducing body burdens.

Conflicts of interest

None.

Acknowledgements

This study was funded by the UK Natural Environment Research Council (NERC): CASE studentship NE/F014139/1, the Institute of Health and Society, Newcastle University, UK, and Fera, Sand Hutton, York, UK. Thanks are extended to Dr David Mortimer, FSA, London, UK for expertise and advice regarding furniture fire safety regulations and dietary exposure to PBDEs. Thanks are also given to the study participants.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.chemosphere.2017.08.062.

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2.5.5 Short discussion of strengths and limitations

This paper provides a summary and discussion of findings for the whole study and presents the indoor dust concentrations for the cohort. It is the first paper to present matched dust and diet intakes for the UK and a world first for matched BDE-209 data for dusts, diets and body burdens. It demonstrates a wide variation in exposures between individuals and highlights key exposure sources and body burden indicators.

This paper was initially rejected due to the small cohort size and because data had been previously published. In response to these points (i) it would not have been possible to collect and examine with as much detail with a larger cohort, and (ii) it was important to include the previously published data to provide the overarching examination of participants PBDE exposures and links to body burdens.

My finding that raised BDE-209 concentrations in UKs dust did not lead to BDE-209 body burdens that were a concern to health is good news. For adults the BDE-209 does not appear to be metabolising/ debrominating to less brominated PBDEs at levels of concern to health either. Recent studies suggest that the hydroxy metabolites of PBDEs may be more potent endocrine disrupters that their parent compounds (Wang *et al.*, 2012; Lyche *et al.*, 2015).

The paper provides further evidence that whether dust or diet is the primary exposure source for an individual depends on the congener in question, the loading of PBDE in the individuals dust or food items and the amounts ingested.

As older soft furnishings and older electrical items are replaced, indoor sources of PBDEs would be expected to reduce considerably, although as a result of the fire safety regulations, alternative flame retardants will be present instead.

Although milk and dairy products are also known to be dietary sources of PBDEs we did not find an association with their portion number and duplicate diet PBDE concentration. This may be because the association was obscured by the greater contribution from meats. I found no association between food types and BDE-209 in

the duplicate diets. It is interesting to consider why a significant correlation was found for meat but not dairy food groups. This may be linked to contaminant retention in the fat of an animal, and PBDE half-lives. Milk (in this case = dairy products) is a transitional matrix which reflects recent consumption of food or feed and some element of the normal body fat burdens. The contaminant profiles for stored fat (*i.e.* meat) will be different and reflect the steady-state (contaminant/fat and half-life) in the tissue.

It is also noteworthy that the breast milk sample with the highest $\sum BDE_{3\text{-}7}$ concentrations was matched with the duplicate diet with the highest $\sum BDE_{3\text{-}7}$ which contained a large portion of fish (Cod) caught in the local River Tyne. In 2008 we reported concentrations of $\sum BDE_{3\text{-}7}$ in cod caught in the Tyne estuary (0.41 µg kg^{-1}) to be four times greater than concentrations reported in the FSA's Brominated Chemicals in UK Fish Study (0.10 µg kg^{-1}).

I tested for trends with indoor dust BDE-209 concentrations to see whether they could be influencing the diet samples, but an association was not apparent. It may be that BDE-209 contamination may be entering the food from airborne dust particles or dust via dermal contact during packaging, processing or preparation prior to being purchased by the consumer. Recent research has found banned BFRs including PBDEs in kitchen utensils as a results of manufacture including recycled plastics introducing another potential source of BFRs in diet (Samsonek and Puype, 2013).

Finding average infant intakes below recommended MOE is a wakeup call that should not be ignored. Our finding of one in ten households with infant intakes below recommended MOE means there will undoubtedly be many more like it in the UK. Ideally I would collect serum samples from the infants of parents in the study to ascertain the relationship between their estimated dust exposures and body burdens. Unfortunately the amount of blood required (60 ml) may make ethical approval for such work difficult to achieve. Higher exposures to PBDE in homes will reduce in time as older furniture and carpets are replaced, but how safe are replacement chemical fire retardants?

My dust sampling method used the standard protocol used in (Harrad *et al.*, 2008b; Harrad *et al.*, 2008c) but rather than collecting only from the floor, the area most often occupied by the participant including desk top, chairs and beds was included in the same sampling time and area. This deviation maybe the reason I reported slightly higher dust: diet ratios than these studies. Another explanation could be their use of UK TDS data for dietary intake estimations which we found to be greater than dietary intakes determined from duplicate diet PBDE concentrations for study participants.

Dust ingestion rates are more uncertain than inhalation rates or food intake rates for which average values are available. Dust ingestion depends on the dust loading of an environment and the activity of the person under consideration, both of which vary widely. Evidence of PBDE concentrations in indoor dusts and air in the UK has grown in recent years, along with estimates of human exposures via indoor dusts, but only a few studies (D'Silva, 2005; Thomas, 2006; Abdallah and Harrad, 2014) have investigated UK human body burdens. These were discussed in Section 2 of the thesis (Bramwell *et al.*, 2014).

Chapter 3 Discussion

3.1 Principle Findings

This study has provided a unique data set of human PBDE body burden concentrations, including BDE-209 concentrations with matched intake estimations for dust and diet. Additional detailed information from questionnaires, diaries and surveys provided information on key predictors of raised PBDE concentrations in diet, indoor dusts and body burdens.

The principle study findings with respect to the objectives and hypotheses were as follows.

3.1.1 PBDE body burdens

Objective: *Investigate human PBDE body burdens for a UK cohort and compare with previous UK and international measurements.*

Hypothesis 1. *Serum concentrations of PBDE have not reduced since they were banned from use in the EU.*

The serum PBDE concentrations measured for this cohort ranged between 1.0 and -16 ng g^{-1} lipid with median (UB) 4.0 ng g^{-1} for $\sum BDE_{3\text{-}7,}$ and between <1.2 and–20 ng g^{-1} lipid for BDE-209. The median and maximum concentrations were lower than those for a 2003 UK cohort, which had a range of 0.63 -420 and median 5.6 ng g^{-1} lipid for ∑PBDEs (Thomas, 2006). This finding therefore suggested a modest reduction in UK body burdens since implementation of use restrictions for PBDEs in 2004. My cohort's median body burden PBDE measurements were approximately one to two orders of magnitude lower than those reported in North America and at the mid to lower end of European data.

PBDE concentrations for the breast milk samples in this study ranged between 1.3 and 21.0 ng g^{-1} lipid, with a median (UB) of 5.7 ng g^{-1} for $\sum BDE_{3\text{-}7.}$ The range for BDE-209 was between 0.2 and 1.0 with median 0.5 ng g^{-1}. These findings were very similar to three previous UK studies. A slight reduction in the median $\sum BDE_{3\text{-}7}$ may be indicated by the two most recent studies that had samples collected in 2009-2012 versus 2001-2003. Estimations of the intake of BDE-47 and BDE-99 intake via

breast-milk for concentrations measured in this study were at the top end of European intakes estimates reviewed by EFSA (2011). BDE-153 and BDE-209 levels were closer to the centre of the European range.

Objective: *Determine whether the elevated BDE-209 concentrations measured in UK dusts have resulted in raised UK body burdens of BDE-209.*

Hypothesis 2. *High concentrations of BDE-209 in indoor dust in the UK compared with mainland Europe have led to higher BDE-209 body burdens.*

The chemical properties of BDE-209 indicate they should have low bioaccessibility. This was borne out by the relatively low concentrations I measured in body burdens compared with environmental samples.

The finding that BDE-209 body burdens were not elevated above European levels was welcome, given the considerably higher BDE-209 levels measured in UK dusts compared with those in mainland Europe.

3.1.2 Estimates of PBDE intakes via dust and diet, and guidance recommendations

Hypothesis 3. *UK intakes of PBDE are not a concern to health.*

Acceptable intakes rates for PBDE have been suggested by US-EPA and EFSA rather than acceptable body burden concentrations in order to protect human health. It is difficult to regulate or take action to reduce body burden, but food and other sources of exposure can be regulated and therefore controlled to some degree. Both average and high PBDE intake estimates for sum intake via diet and dust for the study participants were compared with the most recently developed health reference values; EFSA's $NOAEL_{10}$s for BDEs-47, -99, -153 and -209. All my adult participants PBDE exposures were found to be within recommended MOEs.

However, estimated infant exposures (ages 1.5 to 4.5 years) showed that the BDE-99 intake for one of the households did not meet EFSA's recommended margin of

exposure and another two households were borderline for high level dust and diet intake.

Infant intake of PBDEs via breast-milk was estimated from concentrations in breast-milk samples collected for the study. Although these were well within US-EPA RfDs for congeners considered, comparison with more recent EFSA $BMDL_{10}$ was less favorable. Potential intakes of concern were indicated for BDE-47, -99 and -153. It should be noted that dust exposure was not included in this comparison and although dust intake of infants less than six months old will be lower than that for adults and older infants, it is unlikely to be negligible.

Objective: *Investigate associations between paired serum and breast milk concentrations*

Hypothesis 4. *PBDE concentrations in breast milk can be used to predict serum concentration*

Unlike the serum samples, the breast milk samples in my study were not necessarily collected in a fasted state. Milk is a transitional matrix which is more likely to reflect recently consumed food than background body burden (Pratt *et al.*, 2013). I found limited correlations between congeners in serum and breast milk, possibly as a result of variation in transfer of PBDEs from serum to milk varying between different congeners. I noticed average serum/milk ratios generally increased with molecular size and hydrophobicity for the most abundant congeners BDE-47, BDE-99 and BDE-209. The congener with the longest human half-life, BDE-153, had greater concentrations in milk than serum for this study. BDE-153 proportions are often higher in biological samples compared to abiotic samples or the original technical product. These higher proportions are found in the adipose tissue where lipophilic contaminants are stored due to its longer half-life. Interestingly, I found men to have significantly higher serum BDE-153 than women in the study. The reason for this is not clear but may be linked to the women generally having higher BMIs and thus the ability to store PBDEs in fat reserves which dilutes serum PBDE concentrations, the PBDE depuration effect during pregnancy and breastfeeding and the longer human half-life of BDE-153.

3.1.3 Key exposure sources

Objective: *Measure matched indoor dust and 24 hour duplicate diet PBDE concentrations for the same cohort.*

Aim: *Determine whether diet or dust was the greater exposure source for individual PBDEs and individual participants.*

Hypothesis 5. *Diet is an important indicator of PBDE body burden*

Diet was the major exposure sources of tri-hepta BDEs for the participants in this study, and meat was the major source of tri-hepta BDEs in diets. The fish and seafood food group contained higher levels of PBDE, however my cohort were not high fish consumers. The median number of meat portions consumed per week being 7 whereas the maximum number of fish portions was 3.5.

Hypothesis 6. *National estimations of PBDE intake calculated from information on PBDE concentrations in common foodstuffs and national consumption survey data are suitable to estimate individuals dietary PBDE intakes.*

Although national estimations of PBDE dietary intakes for adults were a little higher than those I measured in my duplicate diets they provide a useful, appropriately conservative estimate. It is also acknowledged that participants have a tendency to adopt a healthier than normal diet when collecting duplicate diet samples. Consequently consumption of fatty food types may not be fully reflected in the DD samples resulting in lower exposure estimates.

Objective: *Estimate proportional exposure to indoor dusts using activity diaries.*

Objective: *Investigate relationships between room contents and usage with (i) dust PBDE concentrations and (ii) PBDE body burdens using room contents, surveys and activity diaries.*

Hypothesis 7. *Indoor exposures to PBDEs are an important contributor to overall PBDE exposure.*

Hypothesis 8. *PBDE levels in dust can be predicted from information about the vehicle or rooms' contents and usage.*

Bedrooms were the rooms where the greatest PBDE intake was estimated to occur (33% to 43%) due to more time being spent there rather than bedrooms having particularly high dust concentrations. Workplaces (19-20%) and living rooms (13-21%) were the environment providing the next greatest intakes for $\sum BDE_{3-7}$ and vehicles for BDE-209 (20%). Significant associations were found between congeners from the Penta BDE product in serum and bedroom dust and BDE-47 in living room dust and breast milk. Dust was the major source of BDE-209 for study participants, and rooms with carpets or rugs over 20 years old had higher BDE209 concentrations. Rooms with items of soft furnishings over 20 years old or adhering to USA fire safety standard Technical Bulletin 117 had higher concentrations of congeners from the Penta BDE technical product. More frequent dusting was significantly correlated with lower PBDE concentrations in dust.

3.2 Strengths and Limitations

3.2.1 Study design

Previous studies of this kind have usually considered only one or two elements of this programme, such as dust and breast milk or diet and serum. No previous UK study had used such paired sampling. The real strength, and the novel aspect of my study, is the comprehensive sampling plan and the state of the art analytical capabilities, exposure modelling and human health risk assessment. These were made possible by the multidisciplinary team of scientists making up the research and supervisory team.

The decision to study cohabiting couples rather than unconnected individuals was initially taken to reduce analytical expenses by having shared indoor environments, to the cost of more robust statistics in the study. During the course of the study, similarities and differences between couples became apparent and added a further dimension of interest to the findings.

The small cohort size also meant that I could collect an unusually comprehensive data set from them. I was able to carry out all participant liaison, providing instructions, and collecting samples. This minimized variation in physical sample

collection and handling. The close relationship with participants provided me with an in-depth knowledge of each participant's homes, diet, activities and exposure history. The downside of the small cohort size was a lack of robustness of the statistical findings, and follow-up work with larger sample numbers would be needed to improve the statistical validity of the findings. The study philosophy was to find out as much detail as possible about the volunteers to understand the links rather than try to represent averages for the UK as a nation.

One unique strength of this study was the measurement of BDE-209 in all four matched matrices, a difficult feat for the biological samples where concentrations are low and precautions are necessary during all stages of the sampling, extraction and analytical process to avoid contamination.

The longitudinal data for the two repeat sample collection weeks provided demonstrations of the variation in PBDE loading between sampling points, without proportional changes between congeners, where diet and environments are stable.

The matched serum and breast milk data provided an opportunity to explore differences between these two matrices as body burden measurements.
A number of additional samples and analyses would have made excellent additions to the study had time and finance been infinite.

The initial study design had included the assessment of associations between hormones in serum indicating fertility, insulin production and thyroid function and PBDE concentrations in serum. Ultimately this was not possible to pursue as part of the study, due to hormone analysis requiring repeated sample collection in order to mediate for daily and monthly variations in concentrations, and the additional funding that would be required to undertake this. Such exposure response indicators would have been a valuable addition to the study's dataset.

XRF measurements of Br in electronics and soft furnishing items in rooms and vehicles of participants would have helped clarify Br sources in the indoor environments surveyed. However, the method would not be able to differentiate between Br in other BFRs or azo dyes. To fully characterize exposures from

furnishing items, collecting and testing small samples of foams/ fabric lining from soft furnishings would allow analysis and identification of flame retardant treatments used on the item.

Measuring PBDE concentrations in indoor and outdoor spaces frequently used by the participants, as well as their vehicle air would enhance the intake estimations. This could be done either passively for the room, or using an active systems collecting either room air or personal individual uptake.

Measuring serum PBDE concentrations of the infants of participant parents would provide helpful evidence of associations between infant serum and matched BM concentrations for comparison with intake data estimated for 1.5 to 4.5 year olds. Similarly, serum PBDE concentrations for the nursing infants would be a very interesting addition but would be unlikely to receive ethical approval.

3.2.2 **Quality Control**

The laboratory data quality for the study was maximized by samples being analysed at state of the art laboratories at Fera and Birmingham University laboratories, using the best available techniques. Quality assurance parameters such as limits of detection (LODs), precision, linear range of measurement, and recoveries characteristics all adhere to accepted EU standards for analysis. My work at the laboratories was undertaken after training and under strict supervision. Fera take part in inter-laboratory comparison studies such as POPs in Food 2012 (Bruun Bremnes *et al.*, 2012).

3.2.3 **Study challenges**

Using the NHS clinical research facility (CRF) for collection of blood samples meant participants became NHS patients and required ethical approval for the study via the NHS National Research Ethics Service. This is a more rigorous procedure than for University Ethics, which with hindsight, would have been sufficient and less time consuming, and could have been achieved using an agency nurse to collect the

bloods. However, use of the facility did mean I had access to specialist body fat mass measuring equipment, and a centrifuge for the blood samples and freezers for storage prior to transport. Overall, it would have been much easier for all of the participants to have had their samples collected at home rather than requiring their family to travel into the city centre first thing in the morning from across the region.

Recruiting participants to commit to taking part in such a time consuming and intrusive study was a challenge. Trying to recruit participants with a broad range of occupational exposures as well as breast feeding mothers required visiting many different businesses and baby or breastfeeding groups.

The conduct of the systematic review was a detailed and time consuming process in order to ensure the full requirements of a systematic review were met. Guidance from publications and colleagues, helped with this task. This was an area where IHS colleagues had a great deal of expertise and for this I was extremely grateful.

During the data analysis and manuscript writing for the dietary exposure paper (Section 2.3) my knowledge of POPs beyond PBDEs was greatly expanded, particularly their history and regulation, and also my understanding of the intricacies of dietary exposure assessment.

3.1 Health Implications

There are no published guidelines for 'safe' human serum PBDE concentrations, however my cohort's levels were similar to those found to be associated with some endocrine disruption effects, e.g. a Japanese study that reported a strong inverse correlation and between BDE-153 concentrations in serum and sperm count measured serum $\sum BDE_{3\text{-}7}$ concentrations of 1.1-8.6 ng g^{-1} lipid in 10 study subjects (and range 0.37 – 1.1 ng g^{-1} lipid BDE-153) (Akutsu *et al.*, 2008). A Korean study of 105 pregnant women with a mean $\sum BDE_{3\text{-}7}$ concentration of 2.13 and inter quartile range 1.35-4.34 ng g^{-1} lipid found a positive association with $\sum BDE_{3\text{-}7}$ and T_4 and a significant negative association with BDE-47 and T_3 (Kim *et al.*, 2013). Evidence of

human health effects arising from PBDE exposure is limited, with some inconsistent findings on altered thyroid function (Kim *et al.*, 2014).

The small reduction in UK body burdens suggested by my data suggested that the use restrictions are working but that the pace of change is slow. A larger sample number would provide a better indication of a shift in UK body burdens. What is of continuing concern is that PBDEs have simply been exchanged for different chemical flame retardants, which are likely to have their own health concerns in future. This cycle is likely to continue until the approach towards reducing fire risk is changed to more sustainable methods. This could be by making consumer products from using less combustible materials, or using fire retarding chemicals that are chemically joined to the polymers they protect.

BDE-209 has a short estimated human half-life (a few days to weeks) but there is evidence indicating it may de-brominate to BDE-153 in humans (Abdallah and Harrad, 2014a), a congener of greater concern to health and estimated human half-life of several years. Hydroxy-metabolites of PBDEs have been indicated to have greater endocrine disruptive effects (Lyche *et al.*, 2015). Thus the potential impacts of BDE-209 exposure are still being uncovered.

PBDEs are just one of many lipophilic endocrine active substances to which humans (and all living beings) are exposed to at varying levels. The scientific evidence is still far off understanding the 'mixture effects' from interactions between these substances, which are always found together in real life situations.

3.2 Policy Implications

The history of chemical flame retardant usage and regulation over the last half century follows a repeating pattern. A product is introduced, for example FireMaster BP-6 (Safe *et al.*, 1978). Significant health concerns arise regarding the main constituents, PBBs. PBBs use is heavily restricted and replacement products are required in-order that petroleum based items, such as PUF, can continue to meet fire safety regulations. One such replacement was Bromkal -70-5DE a 'Penta-BDE' product. Pre-use toxicity testing for replacements is non-existent or inadequate.

Independent toxicologists, epidemiologists and exposure scientists discover significant health concerns, use of the substance is effectively banned and replacements are required because PUF still needs treating to meet fire safety regulations. TDCPP was one of the products used to replace Penta-BDE. The scientific community realized they had seen it before. TDCPP (a.k.a. Tris) was used in the 1970s in children's sleepwear until concerns regarding its carcinogenicity resulted in its removal in 1978 (Gold *et al.*, 1978). Despite the known health risks associated with TDCPP, how did it find its way back into common usage? A recent BFR meeting revealed a quickly growing set of halogenated and organophosphate flame retardant chemicals currently in use.

PBDE use may now be heavily restricted in many global regions, but its legacy and that of other such chemicals will continue for decades. Monitoring of environmental and biomonitoring trends feeds into expert panels such as COT and EFSA and into policy via reviews of food safety or of methods of reducing fire toxicity. Sometimes – as in the case of TDCPP – discussions can be well into the future.

3.3 Future research

The detailed information gathered for this study has revealed some interesting results. A larger study would improve the statistical robustness of these findings, perhaps with a longer duplicate diet collection period. Including some different occupations such as taxi drivers, train or airline staff, electronics recycling staff and fire fighters would be of beneficial due to their perceived greater exposure to PBDEs and their replacement chemicals.

During the course of this study a number of topic areas have been highlighted that would greatly benefit from additional research. Several EU countries and the USA have large scale biomonitoring programs which allow investigation of chemicals of concern and monitor impacts of legislation, allowing population level health impacts to be identified. Such a programme in the UK would be a great asset to those involved in developing policy for health protection.

US-EPA RfDs for acceptable PBDE intake levels are considerably higher (e.g. 200 ng kg^{-1} d^{-1} for BDE-99) than EFSA's $BMDL_{10}$s (9.6 ng kg^{-1} d^{-1} for BDE-99) even

when taking into account the different manner of use of these guidance values. New guidance values are required for PBDEs replacement chemicals and PBDE values are in need of updating to include more recent epidemiological and toxicological data.

In this study I have characterized my cohorts' risks from individual PBDEs, however humans are exposed to a large number of environmental chemicals every day, some already known to cause health effects and others with some unknown toxicology. The effects of interaction between these substances and cumulative effects on biological targets are challenging areas of research need of elucidation. The metabolites of individual chemicals should also be added to this exposure matrix.

The wider cost benefit of fire toxicity reduction by halogenated flame retardant chemicals is questionable with no clear data available. Smoke alarms and less smoking in homes have arguably made the greatest reductions in death and injury from domestic fires (Shaw *et al.*, 2010). Perhaps research into, and then use of, alternatives to chemical flame retardants would be of the greatest benefit to humans and the wider environment.

3.4 Conclusions

This thesis provides a snapshot of ten couples' PBDE exposures from indoor dusts and diet and their concurrent body-burdens. In addition PBB concentrations in matched serum, breast milk and duplicate diet samples are reported as well as concentrations of PCDD/F, PCBs, PBBs and PBDD/F in duplicate diets.

I used a cross sectional and purposive sampling strategy to provide a snap shot of PBDE exposures and body burdens for individuals with expected high, average and low exposures. By comparing individuals with expected divergent exposures I aimed to reveal the factors influencing differences between body burdens.

Differences in body burdens between individuals in the participant couples, between genders, between body burden matrices, over time, between diet types and furnishings and behaviours were reported for the cohort. The findings have been

compared with the literature and explanations for these differences have been explored.

The findings add to a growing evidence set of data and literature identifying the presence of chemicals of concern in our indoor and outdoor environments, stored in our bodies and being passed on to our children in the womb and during breast feeding.

Despite legislation effectively banning the use of PBDEs in new products the long life span of the consumer products in which they were used, along with environmental and biological persistence, means reduction in exposure is slow.
We are also reintroducing PBDEs back into home in new products via plastics recycling. PBDEs, their predecessors and successors will be circulating in our homes and food chains for many years to come.

3.5 Dissemination of Findings

In addition to the journal articles presented earlier, elements of the study have been presented at the following meetings. Abstracts and posters are presented in Appendix B.

- 2009, North East Postgraduate Conference, Newcastle, UK; UK's largest annual postgraduate conference for medical biosciences, poster presentation *'Diet and indoor environments as predictors of human body burden of PBDE'*;
- 2010, Institute of Health & Society Postgraduate Conference, Newcastle University, Newcastle, UK; informal in house meeting, 30 delegates, oral presentation *'Diet and indoor environments as predictors of human body burden of PBDE'*;
- 2011, Food and Environment Research Agency Staff Meeting: York, UK, informal in-house meeting, *'Diet and indoor environments as predictors of human body burden of PBDE'*;

- 2011, Safety Health Environment (SHE) Conference, Newcastle, UK; 300 delegates from the NE region and beyond, mostly SHE practitioners; invited speaker on *'Brominated Flame Retardants -a burning issue'.*
- 2012, Institute of Health & Society and Institute of Aging joint Research Day Newcastle University, Newcastle, UK; oral presentation *'Diet and indoor environments as predictors of human body burden of PBDE'*.
- 2012, Institute of Health & Society, Research Day Newcastle University, Newcastle, UK; oral presentation *'Diet and indoor environments as predictors of human body burden of PBDE'*.
- 2013, International Symposium on Flame Retardants BFR2013, San Francisco, USA, 300 delegates, international experts from industry, governments and academia meet to exchange latest research results and to propose measures to reduce risk from the use of flame retardants; oral presentation; A *Matched PBDE levels in Serum, Breast milk, Dust and Diet for UK Couples'.*
- 2013, Persistent Organic Pollutants Network Conference, Birmingham, UK, 100 delegates, mostly UK based regulators and academics with some international speakers, oral presentation; A *Matched PBDE levels in Serum, Breast milk, Dust and Diet for UK Couples'.*
- 2013, 7th UK & Ireland Occupational & Environmental Epidemiology Meeting, London School of Hygiene and Tropical Medicine, 100 delegates with interests in environmental and occupational epidemiology. Oral presentation; *Matched PBDE levels in Serum, Breast milk, Dust and Diet for UK Couples'.*
- 2013, Research in Progress Meeting, Medical Toxicology, Newcastle University, Newcastle, UK; informal meeting to share findings and discuss

ideas, invited oral presentation; *Matched PBDE levels in Serum, Breast milk, Dust and Diet for UK Couples'*

- 2014, 34th International Symposium on Halogenated Persistent Organic Pollutants; the leading international conference for scientists, regulators and exhibitors presenting recent advances in all areas of Halogenated Persistent Organic Pollutants, 800 delegates; poster presentation; '*UK Dietary Exposure to PBDEs, PBBs, PCBs, PBDD/Fs and PCDD/Fs: Comparison Of Results From 24 Hour Duplicate Diet With Total Diet Study Estimation and Health Risk Assessment'.*
- 2014*,* 8th UK & Ireland Occupational & Environmental Epidemiology Meeting, Manchester, UK; Oral presentation; *PBDE Levels in Dust, Diet, Breast Milk And Serum for UK Couples.*
- 2015, 8th UK & Ireland Occupational & Environmental Epidemiology Meeting, Imperial College London, UK poster presentation; *'UK Dietary Exposure to PBDEs, PBBs, PCBs, PBDD/Fs and PCDD/Fs: Comparison Of Results From 24 Hour Duplicate Diet With Total Diet Study Estimation and Health Risk Assessment'*
- 2016, 36th International Symposium on Halogenated Persistent Organic Pollutants, Florence, Italy; oral presentation; *'Key predictors of human PBDE body burden for a North East UK Cohort'*
- 2016 *International Society for Environmental Epidemiology's A*nnual Scientific Conference, Rome, Italy, over 1200 delegates, mostly academics and students, poster presentation; *Comparison Of Results From 24 Hour Duplicate Diet With Total Diet Study Estimation and Health Risk Assessment'*

- 2016 Applied Epidemiology Day, Newcastle University, Newcastle, UK; in house conference, 50 delegates; oral presentation; *'Key predictors of human PBDE body burden for a North East UK Cohort'*
- 2017, 9th UK & Ireland Occupational & Environmental Epidemiology Meeting, University of Birmingham, UK; oral presentation; *'Key predictors of human PBDE body burden for a North East UK Cohort'*
- 2017, International Symposium on Flame Retardants BFR2016, York, UK, 250 delegates, international experts from industry, governments and academia meet to exchange latest research results and to propose measures to reduce risk from the use of flame retardants, poster presentation, *'Predictors of PBDE body burden for a UK cohort'*

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Appendix A

Candidates contributions to papers and co-authorship forms

Title: **Associations between human exposure to polybrominated diphenyl ether flame retardants via diet and indoor dust, and internal dose: A systematic review.**

Authors: Bramwell L, Glinianaia SV, Rankin J, Rose M, Fernandes A, Harrad S, Pless-Mulloli T.

Journal: Environment International

Date of publication: April 2016

Contribution of the candidate to this work

- Developing the search strategies and executing searches with assistance from IHS information specialists.
- Developing the inclusion and exclusion criteria.
- Abstract scanning (100% of papers).
- Adapting study quality criteria from Roth and Wilks (2014).
- Data extraction (100% of papers).
- Narrative synthesis of findings, theme extraction.
- Overall adherence to preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidance (Moher et al., 2009).
- Preparing the draft manuscript, tables, figures and references and editing in accordance with co-authors.
- Responding to reviewers' comments, final editing and proof reading.

Newcastle University

SUBMISSION BY STAFF CANDIDATES FOR THE DEGREE OF PHD BY PUBLISHED WORK

CO-AUTHORSHIP FORM

This form must accompany any submission of a joint authored publication for the degree of Doctor of Philosophy on the basis of published work.

A candidate should submit a separate form for each jointly authored work which is submitted for the degree.

TITLE OF PUBLICATION (article, book, chapter, monograph) :

Associations between human exposure to polybrominated diphenyl ether flame retardants via diet and indoor dust, and internal dose: A systematic review

DATE OF PUBLICATION : April 2016

NAME AND VOLUME OF JOURNAL (where appropriate): Environment International 92-93

PUBLISHER (for book, chapter or monograph) _____

EDITORS (chapter only) _____

ISBN (where appropriate) _____

If the work has not been published but has been accepted for publication *please attach a statement from the Editor or Publisher which confirms the intention to publish the work.*

NAMES OF JOINT AUTHORS	INSTITUTION
1. Svetlana V. Gliniania	Newcastle University
2. Judith Rankin	Newcastle University
3. Martin Rose	Fera Science Ltd.
4. Alwyn Fernandes	Fera Science Ltd.
5. Stuart Harrad	University of Birmingham
6. Tanja Pless-Mulloli	Newcastle University

cont/d ...

CONTRIBUTION OF THE CANDIDATE TO THIS WORK (%)

Design of investigation 80_____

Conduct of research 80_____

Analysis of outcome 90_____

Preparation for publication 75_____

This statement should be endorsed by all of the co-authors.

I confirm that the above is a true estimate of the candidate's contribution to this work.

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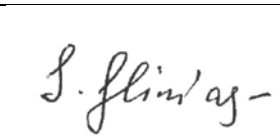
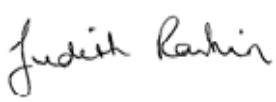
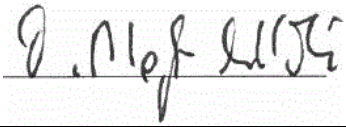
Signature 2			Signature 6	
Signature 3			Signature 7	
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PW8

Title: **PBDEs and PBBs in human serum and breast milk from cohabiting UK couples.**

Authors: Bramwell L, Fernandes A, Rose M, Harrad S, Pless-Mulloli T.

Journal: Chemosphere

Date of publication: April 2014

Contribution of the candidate to this work:

- Developing the study design and successful funding proposal with the help of the supervisory team.
- Ethics applications for the study (IRES, Newcastle University and Fera)
- Recruiting and selecting participants.
- Developing the exposure questionnaire – adapting that used by Wu et al (2008).
- Visiting participants in their homes to collect their consent forms and distribute the literature for the study, and again to collect breast milk samples.
- Liaising with the Newcastle Hospitals Trust Clinical Research Facility to arrange the anthropogenic measurements and collection, preparation and freezing of serum samples. Transfer of samples to the Fera laboratories in York.
- Training in, then carrying out, the sample preparation, extraction, clean up and analysis of PBDEs and PBBs in biological samples by high resolution GC MS at Fera (approximately 50% of samples).
- Transforming the data outputs into body burden measurements (approximately 50% of samples).
- Statistical analysis of data.
- Preparing the draft manuscript, tables, figures and references and editing in accordance with co-authors.
- Responding to reviewers' comments, final editing and proof reading.

Newcastle University

SUBMISSION BY STAFF CANDIDATES FOR THE DEGREE OF PHD BY PUBLISHED WORK

CO-AUTHORSHIP FORM

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A candidate should submit a separate form for each jointly authored work which is submitted for the degree.

TITLE OF PUBLICATION (article, book, chapter, monograph) :

PBDEs and PBBs in human serum and breast milk from cohabiting UK couples

DATE OF PUBLICATION : April 2014

NAME AND VOLUME OF JOURNAL (where appropriate): Chemosphere 116

PUBLISHER (for book, chapter or monograph) _____

EDITORS (chapter only) _____

ISBN (where appropriate) _____

If the work has not been published but has been accepted for publication *please attach a statement from the Editor or Publisher which confirms the intention to publish the work.*

NAMES OF JOINT AUTHORS	INSTITUTION
1. Lindsay Bramwell	Newcastle University
2. Alwyn Fernandes	Fera Science Ltd.
3. Martin Rose	Fera Science Ltd.
4. Stuart Harrad	University of Birmingham
5. Tanja Pless-Mulloli	Newcastle University

cont/d ...

CONTRIBUTION OF THE CANDIDATE TO THIS WORK (%)

Design of investigation 50_____

Conduct of research 70_____

Analysis of outcome 80_____

Preparation for publication 75_____

This statement should be endorsed by all of the co-authors.

I confirm that the above is a true estimate of the candidate's contribution to this work.

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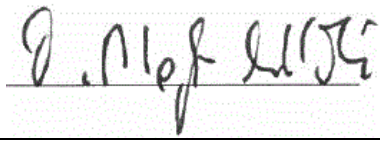
Signature 2			Signature 5	
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PW8

Title: **UK dietary exposure to PCDD/Fs, PCBs, PBDD/Fs, PBBs and PBDEs: comparison of results from 24-h duplicate diets and total diet studies.**

Authors: Bramwell L, Mortimer D, Rose M, Fernandes A, Harrad S, Pless-Mulloli T.

Journal: Food Additives & Contaminants: Part A

Date of publication: January 2017

Contribution of the candidate to this work

- Developing the study design and successful funding proposal for the duplicate diet with the help of the supervisory team.
- Ethics applications for the duplicate diet study (IRAS, Newcastle University and Fera).
- Recruitment and selection of duplicate diet study participants.
- Preparing duplicate diet collection equipment and instructions.
- Visiting participants in their homes to collect their consent forms and distribute equipment and instructions, then again to collect the duplicate diet samples.
- Weighing and preparing duplicate diet samples prior to freezing.
- Transfer of samples to the Fera Laboratories in York.
- Training in, then carrying out, the sample preparation, extraction, clean up and analysis of PBDEs and PBBs in food samples by high resolution GC MS at Fera (approximately 50% of samples).
- Transforming the data outputs into duplicate diet POPs concentrations (approximately 50% of samples).
- Transforming the duplicate diet concentrations into daily POPs intakes and comparing with available health guidelines
- Statistical analysis of data and comparisons with the TDS data.

- Preparing the draft manuscript, tables, figures and references and editing in accordance with co-authors.
- Responding to reviewers’ comments, final editing and proof reading.

Newcastle University

SUBMISSION BY STAFF CANDIDATES FOR THE DEGREE OF PHD BY PUBLISHED WORK

CO-AUTHORSHIP FORM

This form must accompany any submission of a joint authored publication for the degree of Doctor of Philosophy on the basis of published work.

A candidate should submit a separate form for each jointly authored work which is submitted for the degree.

TITLE OF PUBLICATION (article, book, chapter, monograph) :

UK dietary exposure to PCDD/Fs, PCBs, PBDD/Fs, PBBs and PBDEs: comparison of results from 24 hour duplicate diets and total diet studies

DATE OF PUBLICATION : January 2017

NAME AND VOLUME OF JOURNAL (where appropriate): Food Additives & Contaminants: Part A (34)

PUBLISHER (for book, chapter or monograph) _____

EDITORS (chapter only) _____

ISBN (where appropriate) _____

If the work has not been published but has been accepted for publication *please attach a statement from the Editor or Publisher which confirms the intention to publish the work.*

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3. Martin Rose	Fera Science Ltd.
4. Alwyn Fernandes	Fera Science Ltd.
5. Stuart Harrad	University of Birmingham
6. Tanja Pless-Mulloli	Newcastle University

cont/d ...

CONTRIBUTION OF THE CANDIDATE TO THIS WORK (%)

Design of investigation 50_____

Conduct of research 50_____

Analysis of outcome 75_____

Preparation for publication 75_____

This statement should be endorsed by all of the co-authors.

I confirm that the above is a true estimate of the candidate's contribution to this work.

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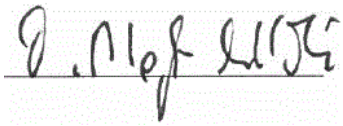
Signature 3			Signature 6	

PW8

Title: **Predictors of human PBDE body burdens for a UK cohort**

Authors: Bramwell L, Harrad S, Abdallah MAE, Rauert C, Rose M, Fernandes A, Pless-Mulloli T.

Journal: Chemosphere

Date of publication: August 2017

Contribution of the candidate to this work

As for the previous two papers and also:

- Developing the study design and successful funding proposal with the help of the supervisory team.
- Preparing study literature, adapting the IARC Food frequency questionnaire, adapting a Newcastle University Human Nutrition Group seven day food diary, developing the room survey, development of the sampling week flow chart and instructions.
- Ethics applications for the study (IRAS, Newcastle University and Fera).
- Recruiting and selecting study participants.
- Preparing of duplicate diet collection equipment and instructions.
- Sourcing and preparing of dust sample collection equipment and instructions.
- Visiting participants in their homes to collect their consent forms and distribute equipment and instructions, then again to collect the duplicate diet samples (participant collected), collect the dust samples (researcher collected) and assist with room surveys, and again to collect breast milk samples.
- Weighing and preparing duplicate diet and dust samples prior to freezing.
- Transferring duplicate diet samples to Fera laboratories in York and carrying out 60% of the analyses, transforming the data outputs into duplicate diet PBDE concentrations and transforming these into daily dietary intakes.
- Training in, then carrying out, the sample preparation, extraction, clean up and analysis of PBDEs in dust samples by GC MS and LC−NI-APPI-MS/MS at the University of Birmingham (100% of samples).
- Transforming the outputs into dust PBDE concentrations

- Transforming the dust concentrations into daily POPs intakes and comparing with available health guidelines
- Statistical analysis of data and comparisons of PBDE intakes from dust and diet.
- Preparing the draft manuscript, tables, figures and references and editing in accordance with co-authors.
- Responding to reviewers' comments, final editing and proof reading.

Newcastle University

SUBMISSION BY STAFF CANDIDATES FOR THE DEGREE OF PHD BY PUBLISHED WORK

CO-AUTHORSHIP FORM

This form must accompany any submission of a joint authored publication for the degree of Doctor of Philosophy on the basis of published work.

A candidate should submit a separate form for each jointly authored work which is submitted for the degree.

TITLE OF PUBLICATION (article, book, chapter, monograph) :

Predictors of human PBDE body burden for a UK cohort

DATE OF PUBLICATION : Available on-line August 2017

NAME AND VOLUME OF JOURNAL (where appropriate): Chemosphere

https://doi.org/10.1016/j.chemosphere.2017.08.062

PUBLISHER (for book, chapter or monograph) _____

EDITORS (chapter only) _____

ISBN (where appropriate) _____

If the work has not been published but has been accepted for publication *please attach a statement from the Editor or Publisher which confirms the intention to publish the work.*

NAMES OF JOINT AUTHORS	INSTITUTION
1. Lindsay Bramwell	Newcastle University
2. Stuart Harrad	University of Birmingham
3. Mohamed Abdallah	University of Birmingham
4. Cassie Rauert	Environment Canada
5. Martin Rose	Fera Science Ltd.
6. Alwyn Fernandes	Fera Science Ltd.
7. Tanja Pless-Mulloli	Newcastle University

cont/d ...

CONTRIBUTION OF THE CANDIDATE TO THIS WORK (%)

Design of investigation 75_____

Conduct of research 90_____

Analysis of outcome 80_____

Preparation for publication 75_____

This statement should be endorsed by all of the co-authors.

I confirm that the above is a true estimate of the candidate's contribution to this work.

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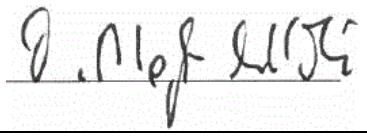
Signature 3			Signature 7	
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PW8

Appendix B

Dissemination of Thesis findings:

Selected abstracts and poster presentations

1. 2009, North East Postgraduate Conference, Newcastle, UK; poster presentation '*Diet and indoor environments as predictors of human body burden of PBDE'- **abstract***

2. 2013, International Symposium on Flame Retardants BFR2013, San Francisco, USA, oral presentation; *'A Matched PBDE levels in Serum, Breast milk, Dust and Diet for UK Couples' -**abstract***

3. 2014, 34th International Symposium on Halogenated Persistent Organic Pollutants; Dioxin 2014, Madrid, Spain; poster presentation; '*UK Dietary Exposure to PBDEs, PBBs, PCBs, PBDD/Fs and PCDD/Fs: Comparison Of Results From 24 Hour Duplicate Diet With Total Diet Study Estimation and Health Risk Assessment' -**poster***

4. 2016, 36th International Symposium on Halogenated Persistent Organic Pollutants Dioxin 2016, Florence, Italy; oral presentation; '*Key predictors of human PBDE body burden for a North East UK Cohort'**- abstract***

5. 2017, International Symposium on Flame Retardants BFR2016, York, UK; poster presentation, *'Predictors of PBDE body burden for a UK cohort'- **poster***

Flame Retardants – Exposure and Body Burden Study

Brominated Flame Retardants (BFRs) added to everyday items have doubtless saved many lives. However some BFRs are Persistent Organic Pollutants (POPs), ubiquitous in the environment and bio-accumulating.

Little is known about the magnitude and exposure pathways of BFRs, but we know the human body burden of BFRs is increasing. BFRs are lipophilic, accumulating in fatty tissue. Mother to child transfer occurs during breast feeding and young children spending time on carpets, exhibiting frequent hand to mouth behaviour have increased body burden. Another route of BFR exposure is food such as oily fish, meat and dairy. Potential adverse human health effects of BFR exposure and body burden are reproductive toxicity, neurotoxicity, immune effects and carcinogenicity.

The aim of this pilot study is to determine whether it is possible to predict a person's body burden and hormone effects of BFRs from a non intrusive study of their diet and indoor environments. Questionnaires are used to model 30 couples' exposures to BFRs from diet, behaviours and work and home environments (e.g. number/age of computers/carpeting, vehicles). Study participants also provide duplicate diets, samples of dust and air from homes and workplaces, blood and breast milk samples, where possible. These are analysed for BFRs to explore relationships between BFR in diet, indoor environments and human body burden and test whether the model can make reasonable predictions. Participants blood samples are also analysed for insulin, thyroid and sex related hormones to explore their relationship with BFRs.

PBDE LEVELS IN DUST, DIET AND SERUM FOR UK COUPLES

Bramwell L[1]*, Fernandes A[2], Rose M[2], Harrad S[3], Pless-Mulloli T[1]

[1]Newcastle University, Institute of Health and Society, Baddiley-Clark Building, Richardson Road, Newcastle upon Tyne, UK; [2]Food and Environment Research Agency, Sand Hutton, York, UK; [3]Birmingham University, School of Geography, Earth & Environmental Sciences, Birmingham, UK

Introduction

Penta- and octa-BDE were banned from use in the EU in 2004[1] with use of deca-BDE in electronics and electrical goods ceasing in 2008[2]. Estimated half lives in the human body for PBDEs range widely from 4-15 days (BDE209) to 6.5 -7years (BDE153) with other congeners mostly below 3 years[3]. UK human body burdens can be expected to decline as a result of these restrictions. In 2006, Harrad and Diamond[4] hypothesised that the indoor reservoir of PBDEs was 'bleeding' out into the wider environment and into food chains. They predicted that the main exposure route would change from indoor dusts to diet as furniture and electronics in our indoor environments were replaced. In 2011 Trudel *et al*[3] compiled and compared data from exposure assessment studies from North America and Europe and concluded that while diet was the dominant exposure pathway to PBDEs for adults with typical body burdens; for individuals with above average PBDE body burdens, dust (via dermal and/or oral routes) could be the dominant exposure pathway.

Data for post-ban serum PBDE concentrations for the UK have been lacking with the only published data being for samples collected in 2003[5]. Furthermore, this study is the first in the UK to examine paired serum samples from cohabiting couples as well as paired duplicate diet and dust samples from their homes, workplaces and vehicles.

The comprehensive study design provides a detailed picture of exposures to further the 'dust versus diet' debate, as well as associations of body burdens with anthropometric measurements for volunteers.

Materials and methods

Households were identified using a screening questionnaire, and encompassed urban and rural locations, couples with 0, 1 or 2 children, and participants with a variety of occupations and diets. Participant numbers were constrained by funding. The study took place in the Northeast of England and was approved by the Durham and Tees Valley Research Ethics Committee.

In 2011, 10 co-habiting volunteer couples each completed a study week. This consisted of food frequency and lifestyle questionnaires to gauge long term exposures, food and activity diaries for that week and room and vehicle surveys (e.g. number/age of computers/carpeting/hours of use). This information was used to evaluate the individual's external exposure to PBDEs. At the end of the week, study participants also provided a 24 hour duplicate diet sample, samples of dust from homes and workplaces, blood sample, and breast milk samples where possible. Duplicate diets were collected for the 24 hours prior to blood sampling and the 50+ mL breast milk samples were collected from the evening of the duplicate diet collection up to the following evening.

Serum samples

Participants visited the Clinical Research Facility (CRF) at Newcastle's Royal Victoria Infirmary for physical measurements such as BMI and body fat mass. On the same visit, blood samples were collected in 6 x10 mL redtop vacutainers, left to coagulate for 20 minutes then spun at 3000 rpm for 10 minutes to separate the serum which was then stored at 18˚C at the CRF laboratory.

Duplicate Diet samples

Participants placed duplicates of any food and dairy drinks consumed over the 24 hour period prior to provision of the blood sample, into a solvent cleaned polyethylene lidded container. The sample was homogenized prior to storage at -18^0C.

Dust samples

Living area (n=10), bedroom (n=11) and vehicle (n=8) dust samples were collected the evening prior to taking the blood samples. Dust samples (n=9) from the workplace of the participants were collected sometime during

the previous week. Dust samples were collected using a DirtDevil DDMHH1 1400 W vacuum cleaner. Dust sampling and storage were conducted according to a previously described standard protocol [6].

Laboratory methods
Serum and duplicate diet samples were extracted and analysed at the Food and Environment Research Agency's (Fera) Laboratories at Sand Hutton, York, UK. Laboratory methods used have been previously described by Fernandes *et al* [7] . Dust samples were extracted and analysed at Birmingham University, UK using methods described by Harrad *et al* [8] The following PBDEs were determined: BDE17, 28, 47, 49, 66, 71, 77, 85, 99, 100, 119, 126, 138, 153, 154, 183 and 209.

Statistical analysis
Serum concentrations are presented in ng/g lipid to enable comparison with previous studies. For statistical analyses, values < LOD were assigned a value equal to LOD * f where f = the fraction of values above the detection limit. Statistical analysis of the results was carried out using R statistical software[9]. Distributions of the concentrations of congeners in different matrices were assessed using Shapiro-Wilk tests. Since they were generally not normal, Spearman's rank correlation coefficient was used to examine relationships between individual congeners.

Results and discussion
Concentrations and percentages of samples with concentrations above the LOD are presented in Tables 1 and 2.

Distributions of the concentration of congeners in different matrices were generally not normal, except for BDEs 17, 49, 66, 85, 100, and 154 in vehicle dusts, BDE28 in living area dusts and BDE209 in duplicate diets.

Table 1 Range and median values for individual congeners measured in serum, duplicate diet and main living area dust samples

	Serum (ng/g lw) n=20				Duplicate diet (ng/g) n=20				Living area dust (ng/g), n=9			
BDE Congener	Median	Min	Max	% > LOD	Median	Min	Max	%> LOD	Median	Min	Max	%> LOD
BDE17	nd	nd	nd	0	<0.002	<0.002	0.004	20	0.90	0.31	8.50	78
BDE28	0.003	<0.010	0.020	15	0.005	<0.002	0.020	75	2.20	0.47	12.10	78
BDE47	0.106	<0.032	0.333	55	0.088	0.035	0.320	100	23.10	5.20	384.60	100
BDE49	0.010	<0.011	0.060	40	0.006	<0.002	0.050	60	0.50	0.30	12.50	78
BDE66	0.010	<0.011	0.060	40	0.006	<0.002	0.063	70	1.20	0.30	13.30	78
BDE71	nd	nd	nd	0	<0.002	<0.002	<0.002	0	na	na	na	na
BDE77	nd	nd	nd	0	<0.002	<0.002	0.004	5	na	na	na	na
BDE85	nd	nd	nd	0	<0.002	<0.002	0.013	20	4.60	1.40	18.20	100
BDE99	0.076	0.021	0.515	100	0.096	0.034	0.443	100	45.70	5.90	388.50	100
BDE100	0.008	<0.01	0.060	30	0.015	0.007	0.078	100	9.00	2.30	76.80	100
BDE119	nd	nd	nd	0	<0.002	<0.002	<0.002	0	na	na	na	na
BDE126	nd	nd	nd	0	<0.002	<0.002	<0.002	0	na	na	na	na
BDE153	0.030	<0.010	0.245	75	0.021	0.008	0.093	100	7.90	0.62	117.60	89
BDE138	nd	nd	nd	0	<0.002	<0.002	0.007	10	na	na	na	na
BDE154	0.001	<0.010	0.030	5	0.010	0.003	0.033	90	13.60	0.60	86.50	100
BDE183	0.002	<0.010	0.030	10	0.013	0.003	0.076	95	9.10	1.51	33.50	89
BDE209	0.037	<0.102	1.818	20	0.785	<0.09	3.130	90	na	na	na	na

nd = non detected above LOD. Serum LODs differ depending on lipid content of sample. *e.g.* BDE17 LODs range from <0.01 - <0.03ng/g.
na = not analysed (not available at this time for BDE209)
For the determination of medians, measurements <LOD have been multiplied by f, the fraction of values above the LOD

Table 2 Range and median values for individual congeners measured in dusts from bedrooms, work areas and vehicles

	Bedroom dust (ng/g), n=11				work area dust (ng/g), n=10				vehicle dust (ng/g), n=8			
BDE Congener	Median	Min	Max	%> LOD	Median	Min	Max	%> LOD	Median	Min	Max	%> LOD
BDE17	0.70	0.33	6.25	82	0.65	0.22	2.80	60	0.90	0.30	3.10	75
BDE28	1.00	0.44	12.40	73	2.70	0.60	28.00	100	1.50	0.50	12.60	87
BDE47	27.00	4.90	1931.10	100	14.30	2.10	416.80	100	23.00	15.80	105.10	100
BDE49	1.20	0.36	62.60	91	0.70	0.36	10.60	90	0.90	0.35	2.20	87
BDE66	1.30	0.82	34.80	91	1.15	0.50	9.50	60	1.60	0.56	3.20	62
BDE85	5.10	1.00	166.40	100	4.55	0.70	27.70	100	7.15	1.80	18.80	100
BDE99	24.10	6.90	3943.10	100	21.95	5.80	776.20	100	43.50	18.30	344.40	100
BDE100	12.00	1.70	551.20	100	8.20	1.00	72.90	100	18.30	1.80	50.40	100
BDE153	10.50	3.50	310.80	100	7.10	0.80	84.30	100	16.90	1.40	117.30	100
BDE154	4.40	0.55	303.50	91	4.20	0.50	80.80	90	8.90	2.90	23.70	100
BDE183	7.30	2.00	31.57	100	6.75	1.51	367.20	90	6.55	2.10	367.20	100
BDE209	na	na	na	na	na	na	na	na	na	na	na	na

na = not available at this time
Measurements <LOD have been multiplied by f, the fraction of values above the LOD

Is diet or dust the primary exposure pathway?
The Spearman's correlations between dust, diet and serum congener concentrations did not reveal the primary exposure for this cohort. Couples in this study demonstrated similar serum congener concentrations unless one of them often stayed away from home for work (different diet and dusts), they had different diets e.g. vegetarian versus high red meat consumer, or one had occupational exposure to foams and furnishings or electronics.

The detail of each participant's exposure history provided by questionnaires and room surveys along with the laboratory measurements allowed interpretation of the individual's PBDE body burden fingerprint and determination of the likely sources of congeners. Both dust and diet were found to be important exposure sources, depending on the individual. Results indicate that the prominence of dust or diet as the major exposure pathway is determined by the interaction between the individual and the source, e.g. all persons fully interact with their food, but only those working in contact with or in close proximity to treated materials interact strongly with them. Further work may be able to determine the relative importance of occupational exposure pathways from dermal contact, hand-to-mouth activity, or dust inhalation and ingestion.

How do this study's results compare with previous UK data?
A summary of serum PBDE concentrations from a national 2003 cohort and this study are presented below in Table 3. When comparing serum PBDE concentrations between Thomas *et al*[10] from 2003 and this study it is important to note that technological advances have significantly reduced the LOD for analyses. So much so that for all congeners except BDE99 this study's maximum value was below the LOD in the Thomas *et al* study. It is also worth noting that the accuracy of blood lipid measurements can vary widely between datasets; larger sample sizes providing more accurate results. By considering ratios of values between the studies we gauged apparent changes in human body burdens over time. Maximum values are significantly different with the median 2003/2011 ratio being 291. The apparent decrease in median concentrations of individual congeners from varied considerably; 8x for of BDE-47, 56x for BDE 153 and 154x for BDE183. The sum of all PBDE congeners measured demonstrated an 18x decrease, indicating an approximate 20 fold reduction in internal exposure to PBDEs in the UK. A study with a greater number of participants would be necessary to confirm this.

This initial exploration of results indicates that UK serum PBDE concentrations appear to have reduced since 2003. Results for the paired breast milk samples for this study and comparison with previously reported UK breast milk PBDE data may be able to corroborate a change in internal exposure. A decrease in internal exposure may be the result of the EU legislation banning use of PBDEs. However, PBDE concentrations in dust for this study are very much in line with previously (more recent) reported UK data for dusts collected in 2003 and 2006[8, 11, 12]. Older dust samples would be useful to help gauge a change in UK dust PBDE concentrations. Previously reported UK duplicate diet PBDE concentrations[13] (n=15) from 1999-2000 indicate an increase (approximately x1.5) in BDEs 47, 99 and 100 in UK dietary PBDE exposure. Results from UK's Food Standards

Agency's Total Diet Studies carried out in 2003 and 2012 (due to be reported in 2013) will clarify whether an increase in UK PBDE dietary exposure has occurred.

Table 3 Summary table for comparisons of PBDE serum concentration in this and a previous UK study.

	Thomas *et al* 2003[10]				This study 2011				Ratio medians
	Median (ng/g lipid)	Range (ng/g lipid)	n	% detects	Median (ng/g lipid)	Range (ng/g lipid)	n	% detects	2003/ 2011
BDE 28	<0.14	<0.14–10	42	27	0.003	<0.01 -0.02	3	15	
BDE 47	0.82	<0.30–180	105	68	0.106	<0.03 - 0.28	11	55	8
BDE 99	<0.16	<0.16–150	63	41	0.076	0.02 - 0.52	20	100	
BDE 100	0.76	<0.17–390	142	92	0.008	<0.01 - 0.06	6	30	97
BDE 153	1.7	<0.26–87	152	99	0.030	<0.01 - 0.25	15	75	56
BDE 154	0.6	<0.15–4.4	132	86	0.001	<0.01 - 0.03	1	5	649
BDE 183	0.3	<0.14–1.8	84	55	0.002	<0.01 - 0.03	2	10	154
BDE 209	<15	<15–240	11	7	0.037	<0.11 - 1.82	3	15	
Total PBDE	5.6	0.63–420	154	100	0.318	0.10 - 3.00	20	100	18
% fat					5.41	2.84 - 9.83			

Acknowledgements
This study was funded by the UK's Natural Environment Research Council (NERC), Institute of Health and Society, Newcastle University, UK and the Food and Environment Research Agency (Fera). Thanks to Mohamed Abdallah, Assiut University, Egypt for training, assistance and advice in dusts analysis, Aileen Mills Newcastle University, School of Biology, UK for assistance with statistical analyses using R software and David Mortimer, Food Standards Agency, London, UK for advice on dietary exposure assessment.

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UK Dietary Exposure to PBDEs, PBBs, PCBs, PBDD/Fs and PCDD/Fs: Comparison Of Results From 24 Hour Duplicate Diet With Total Diet Study Estimation and Health Risk Assessment

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Introduction

Governments and international organisations measure chemicals in food, including nutrients and contaminants, to enable an estimate of consumer exposure through the diet.

Total Diet Studies (TDS) provide dietary exposure estimates for several purposes: baseline information about exposure to new contaminants; monitoring trends in exposure; evaluating efficacy of regulatory controls.

Duplicate diet (DD) or duplicate portion studies provide an excellent measure of an individual's dietary intake over a defined period as an alternative approach to TDS. However, they do not reveal the contribution of specific food types to overall dietary exposure and require a high degree of cooperation from participants. Moreover, effects of local contamination and geology, or individual dietary preferences, may be significant.

Here we present the findings of a 24 hour DD study, collected from 20 adults from northeast England during 2011-12. Results are compared with exposures calculated using corresponding concentrations measured in 19 different food groups for the UK Food Standards Agency (FSA) in 2012[1].

Methods

- Laboratory analysis of both sets of samples was carried out by the Food and Environment Research Agency, Sand Hutton, UK using previously reported methods [2,3].
- TDS dietary exposure estimates were calculated using the FSA's Intake 2 Programme which uses relative proportions of each food group derived from food diaries of 2,000 participants from across the UK.
- The DD results were calculated for individual body weights, and had accompanying food diaries. Findings from the different methods were compared.
- Potential health risks from dietary intake of BDEs were determined using the margin of exposure (MoE) approach used by the European Food Standards Agency (EFSA)[4].
- Chlorinated dioxin WHO-2005 TEF values were used to calculate TEQ concentrations for PBDD/Fs and non-ortho PBBs.

Results

Adult dietary exposure estimates generally showed good agreement between studies (see Table 1).

Table 1: Comparison of estimated adult TDS and measured DD exposures

	BDE-47 (ng kg^{-1} bw d^{-1})	BDE99 (ng kg^{-1} bw d^{-1})	BDE-153 (ng kg^{-1} bw d^{-1})	BDE-209 (ng kg^{-1} bw d^{-1})	PBDD/F/PBB (WHO-TEQ pg kg^{-1} bw d^{-1})	PCDD/F/PCB (WHO-TEQ pg kg^{-1} bw d^{-1})	ICES 6 (NDL PCBs)(pg kg^{-1} bw d^{-1})
Avg. (TDS)	0.2	0.14	0.03	2.56	0.2	0.52	1.84
Avg. (DD)	0.13	0.1	0.02	0.74	0.29	0.27	0.58
P97.5 (TDS)	0.41	0.25	0.06	5.03	0.51	1.08	4.88
P97.5 (DD)	0.59	0.27	0.05	1.76	0.56	1.21	1.77

Figure 1: TDS Food Groups

	Food Group		Food Group
1	Bread	11	Green Vegetables
2	Cereals	12	Potatoes
3	Carcass Meat	13	Other Vegetables
4	Offal	14	Canned Vegetables
5	Meat Products	15	Fresh Fruit
6	Poultry	16	Fruit Products
7	Fish	(17)	(Beverages)*
8	Fats & Oils	18	Milk
9	Eggs	19	Milk & Dairy Products
10	Sugar & Preserves	20	Nuts

* Beverages were excluded from the TDS as they are very low risk for POPs

Discussion

Variation between exposure estimates for BDE-209 may be influenced by the high TDS result for the sugars and preserves food group; 50% of total exposure and milk: 25% of exposure[1]. With these results removed the estimates are close. Where numbers of samples making the food group composite for TDS are low, distortion of results may occur where one or more samples have higher contamination.

While the relative abundance of some individual PBDEs varied between diet types, e.g. BDE-47,-49, -100 and -154 were higher in the DDs containing fish. BDE-209 concentrations were consistent across DD types (lactose free/ vegetarian/ omnivore/ high meat/ high fish). We hypothesise this indicates BDE-209 contamination may arise from food processing/preparation or via contamination with dust.

Conclusion

- Dietary exposures estimated from the TDS gave generally good agreement with actual exposures determined for 24 hour DDs.
- TDS estimates were generally slightly higher than the DD results for both average and P97.5 values indicating an element of conservatism covering diets with greater exposures.
- MoEs for the maximum (upper bound) dietary intakes were estimated as 292, 16 and 192 for BDEs 47, 99 and 153 respectively. According to EFSA, an MoE of 2.5 or above indicated no health concern. The MoE for BDE 209 was 970,000.
- TEQ intakes calculated on an upper bound basis for PBDD/Fs, PCDD/Fs, dioxin-like PBBs and dioxin-like PCBs indicate adult exposures within the Tolerable Daily Intake of 2.0 pg/kg bodyweight.
- For NDL-PCBs, EFSA were unable to derive any health-based guidance values[5]. Their recommendation was that dietary exposure should be reduced and data from projects such as this provide a means to determine whether this is being achieved.

Acknowledgements This study was funded by the UK's Natural Environment Research Council (NERC): CASE studentship NE/F014139/1, the Institute of Health and Society, Newcastle University, UK, the Food and Environment Research Agency (Fera) and Food Standards Agency (FSA). Thanks also to study participants.

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Cod: 4.5014

KEY PREDICTORS OF HUMAN PBDE BODY BURDEN FOR A NORTH EAST UK COHORT

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Introduction

PBDEs are a group of additive flame retardants that were widely used in the late 20th Century until their association with negative human health effects became apparent. Whether dust or diet is the primary exposure source for PBDEs differs between individuals and over time and may be related to occupational exposure, age and extent of local use, countries, with age and over time. In a recent systematic review of associations between human exposure to PBDEs via diet and indoor dust, and internal dose, we concluded three key factors influenced correlations between external PBDE exposure and human body burden: 1) half-life of individual congeners in the human body; 2) proximity and interaction between PBDE source and study subject; and 3) time of study relative to phase out of PBDE technical products[1].

Penta, Octa and Deca are the three technical PBDE mixes of PBDEs. Production and use of Penta and Octa BDE were restricted from use in the EU in 2004[2], with the use of Deca BDE in electronics and electrical goods essentially ceasing in 2008[3]. PBDEs display a range of half-lives in humans with a general trend of shorter half-lives for the higher brominated compounds. Specifically, while estimates of human half-lives for Deca (BDE-209) are just a few days, for the main congeners of the Penta BDE mixture they are around two to four years[4,5]. The main origins of human body burdens of PBDEs can be expected to change over time away from indoor dust towards diet as BFR containing household goods such as soft furnishings and electronics are replaced with items that do not contain PBDEs[6]. The aims of this study were to determine the relative strength of various dietary and indoor environment PBDE exposure predictors for a UK cohort in the North East of the country.

Materials and methods

Participants were selected using a screening questionnaire to include urban and rural locations, and occupations and diets with expected divergent PBDE exposure. The study was approved by the Durham and Tees Valley Research Ethics Committee.

In 2011, the 10 co-habiting volunteer couples each completed a study week with food frequency and lifestyle questionnaires, food and activity diaries and room contents surveys to evaluate individual's external PBDE exposure. Study participants also provided a 24 hour duplicate diet sample, samples of dust from homes (living areas and bedrooms), workplaces and vehicles, 60 mL blood sample, and 50+ mL breast milk samples where possible (see Figure 1). Serum, milk and duplicate diet samples were extracted and analysed for PBDEs at Fera, York, UK, using previously described methods[7]; with dust samples analysed at the University of Birmingham, UK again using previously described methods[8]. The following PBDE congeners were measured: BDE17, 28, 47, 49, 66, 71, 77, 85, 99, 100, 119, 126, 138, 153, 154, 183 and 209.

Results and discussion

Both dust and diet were found to be important exposure sources, dependent on the individual. Exposure and food frequency questionnaires and room surveys, provided detailed insight into each participant's exposure history, and in conjunction with laboratory data, PBDE bioavailability and half-life information, predictors for the body burdens of individuals were assessed. Comparison of PBDE congener fingerprints for sampled matrices indicated serum and milk samples were influenced by Penta congeners with dust dominated by the Deca product (see Figure 2). Rooms with older soft furnishings and exposed foam, or items imported from the USA, demonstrated greater concentrations of Penta mix BDEs in their dust and consequently in the matched participants' body burdens. Duplicate diet samples were influenced by both Penta-BDE congeners and BDE-209.

Acknowledgements
This study was funded by the UK's Natural Environment Research Council (NERC): CASE studentship NE/F014139/1, the Institute of Health and Society, Newcastle University, UK, the Food and Environment Research Agency (Fera) and University of Birmingham, UK. Thanks also to study participants.

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Figure 1: Conceptual Exposure Model/ Study Design

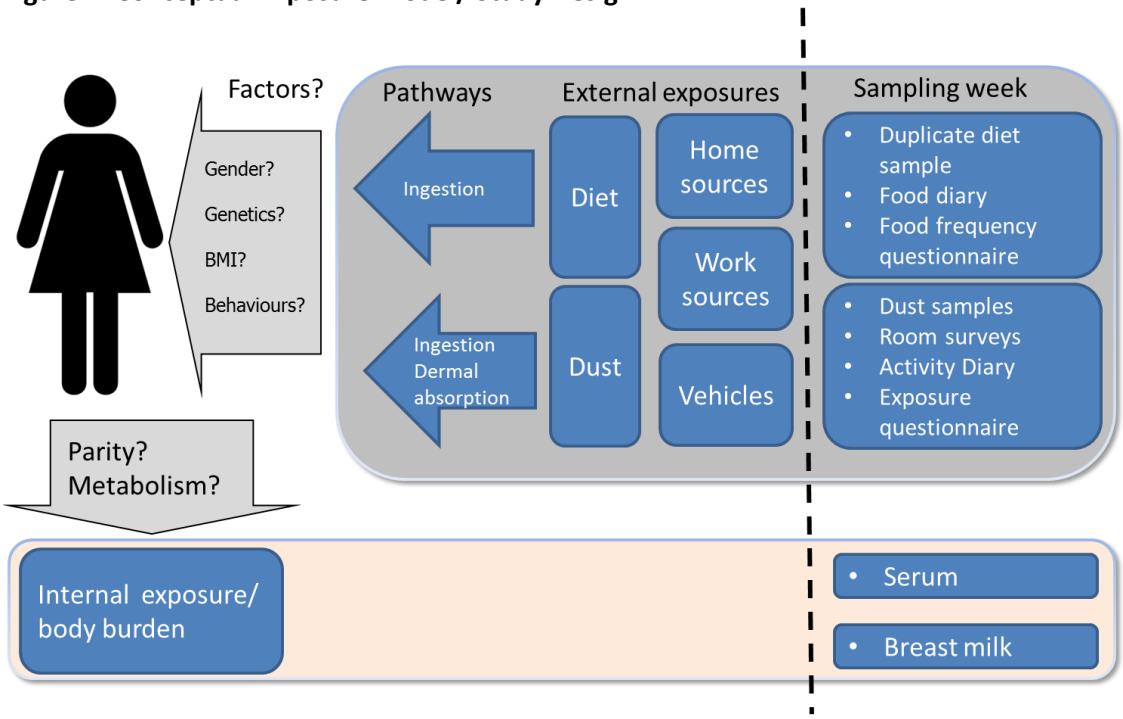
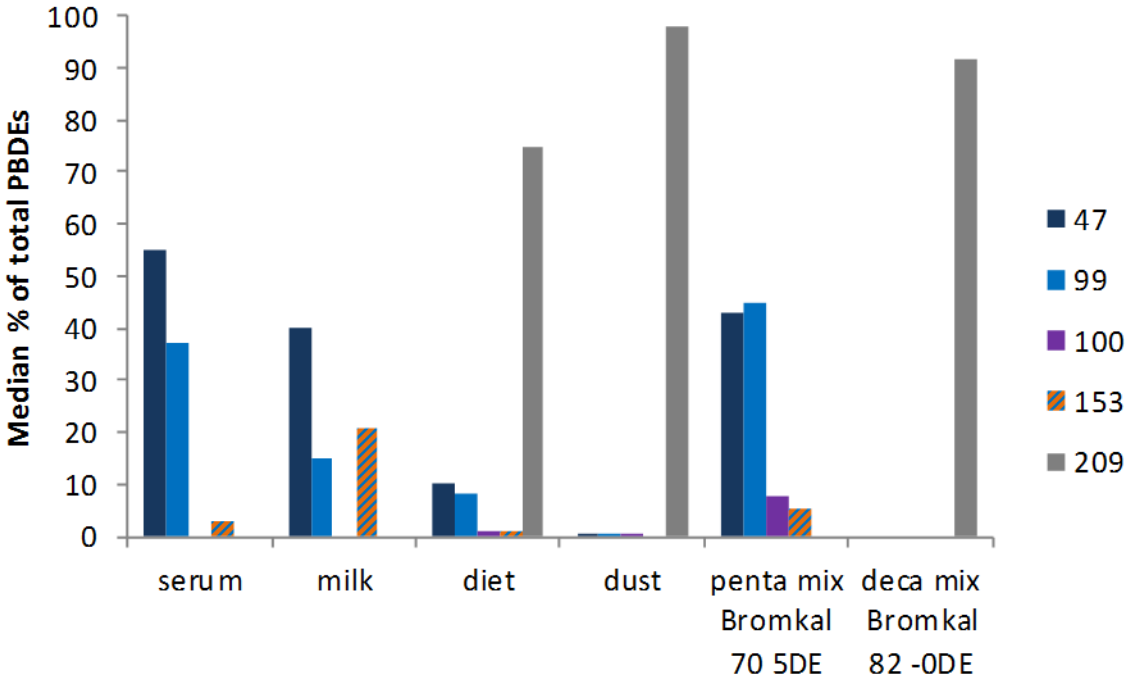


Figure 2: Congener proportions in different matrices for this study and technical mixtures



Predictors of human PBDE body burden for a UK cohort

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Introduction

PBDEs are a group of additive flame retardants that were widely used in the late 20th Century until their association with negative human health effects became apparent. Commercial PBDE products contained mostly penta, octa or deca PBDE congeners and were used in electronics and soft furnishings.

In a recent systematic review of associations between human exposure to PBDEs via diet and indoor dust, and internal dose, we concluded three key factors influenced correlations between external PBDE exposure and human body burden: 1) half-life of individual congeners in the human body; 2) proximity and interaction between PBDE source and study subject; and 3) time of study relative to phase out of PBDE technical products[1].

The aim of this study was to determine the major sources of various dietary and indoor environment PBDE exposures for individuals in a UK cohort, with a view to making recommendations to reduce exposure.

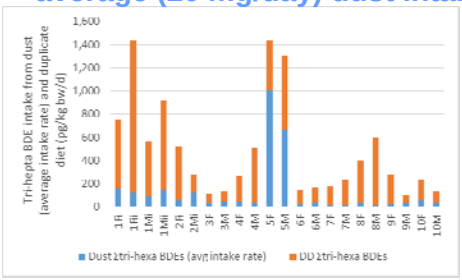
Methods

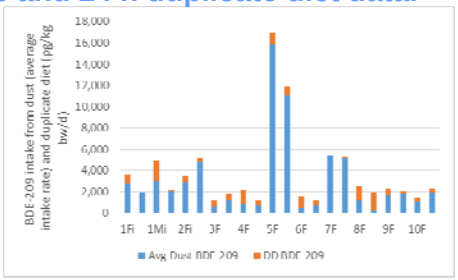
- In 2011, 10 co-habiting volunteer couples each completed a study week with food frequency and lifestyle questionnaires, food and activity diaries and room contents surveys to evaluate their PBDE exposure sources.
- Study participants also provided a 24 hour duplicate diet sample, samples of dust from homes (living areas and bedrooms), workplaces and vehicles, 60 mL blood sample, and 50+ mL breast milk samples where possible.
- Serum, milk and duplicate diet samples were extracted and analysed for PBDEs at Fera Science Ltd, York, UK, and dust samples were analysed at the University of Birmingham, UK using previously published methods[2,3].
- We estimated average and high dust intake[4] for each indoor environment measured and compared the total with estimated intake from diet samples.
- We investigated associations between PBDE body burden and room contents, activities, anthropometrics and diet type.

Results

We measured PBDEs from the Penta commercial mix in all of the samples collected, with ranges of 0.78-12.8 ng/g lw in serum, 1.33-21.0 ng/g lw in breast milk, 0.1-1.4 ng/g lw in the duplicate diet samples, 2,230-3,760 ng/g dust in indoor dusts and 88.1-677 ng/g dust in vehicles. Deca-BDE was measured above the limit of detection in 17% of serum samples, 83% of breast milks, 63% of diet samples and 100% of dusts. Deca-BDE concentrations ranged from <1.13-19.8 ng/g lw in serum, <0.19-1.04 ng/g lw in breast milk, <0.001-3.13 ng/g lw in duplicate diets, 806-65,500 ng/g in indoor dusts and 315-137,000 in vehicles.

Individual participants' PBDE intakes via dust and diet using average (20 mg/day) dust intakes and 24 h duplicate diet data.





Recommendations for reducing PBDE exposure

Discussion

Individuals' estimated daily PBDE exposure via dust ranged from 14 to 1,000 pg/kg bw/d for Σtri–hepta BDEs, and 280-to 15,900 pg/kg bw/d of BDE-209 using an average adult dust intake scenario of 20 mg/d.

Combined exposure estimates via dust and diet revealed total PBDE intakes of 104 to 1,440 pg/ kg bw/d for Σtri–hepta BDEs and 1,170 to 17,000 pg/kg bw/d for BDE-209.

These adult intakes were well within health reference doses suggested by the European Food Safety Authority (EFSA) and the US EPA.

Estimated infant exposures (ages 1.5 to 4.5 years) indicated that BDE-99 intake (using average dust and diet intakes) for one of the households did not meet the EFSA recommended margin of exposure and another two households were borderline for BDE-99 for high level dust and diet intake.

Conclusions

- Diet was found to be the major exposure source for Penta-mix BDEs for this UK cohort.
- Indoor dust was the major source of BDE-209, the greatest exposure being in bedrooms.
- Room contents that were indicated as key PBDE sources were: soft furnishings manufactured during the 1980s and 1990s and newer soft furnishings labelled as meeting the TB117 fire safety regulations from the USA.
- Participants that ate above the group median of meat portions per week had higher serum Penta-mix BDE concentrations.
- More frequent cleaning was associated with lower PBDEs in dust and body burden for participants where exposure was expected to be at the high end of the cohort.

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Acknowledgements

This study was funded by the UK's Natural Environment Research Council (NERC): CASE studentship NE/F014139/1, the Institute of Health and Society, Newcastle University, UK, the Food and Environment Research Agency (Fera) and University of Birmingham, UK. Thanks also to study participants.

Appendix C

Study questionnaires, surveys and instructions

1. Screening questionnaire for volunteers
2. Participant's sampling week checklist
3. Instructions for the room survey
4. Room survey data collection sheet
5. Dust sample collection protocol - thanks to Stuart Harrad, Birmingham University
6. Instructions for collecting the duplicate diet sample
7. Food and activity diary
8. Exposure assessment questionnaire

Name:

Contact email or phone number: **Volunteer Code:**

(Please complete one questionnaire each)

Pre selection questions

1. a) Have you ever been involved in a large fire incident/s
   Y/N
   b) And if so how long ago was the most recent incident?
   <1 yrs, 1-5 yrs, 6-13yrs, >13yrs

2. If you are working what kind of work do you do? E.g. taxi driver, secretary, call centre operative, joiner, sales person

3. What is your workplace environment? e.g. car, office, workshop, factory, shop?

4. How much time do you usually spend in a vehicle each day
   0, < 0.5 hour, 0.5 - 2 hours, >2 hours

5. How many flights and longer journeys (over 4 hours) on boat, train, bus, coach or car have you taken in the last year?
   0, <5, 5-10, >10

6. How often in a month do you eat oily fish such as salmon, trout, anchovies, sardines, mackerel, herring, eel, sprats, kippers?
   0, <2, 3-6, >6

7. a) How often in a month do you eat any meat?
   0, <5, 5-10, >10
   b) Do you eat the skin/fat?
   Y/N/sometimes

8. a) How often in a month do you eat dairy (anything other than a little milk in tea or coffee)?
   0, <10, 10-30, >30
   b) Do you generally eat low fat or full fat milk, yoghurt and cheeses?
   LF, FF, both

Practicalities

1. Will you and your employer allow the researcher to take a dust sample in your workplace (e.g. vacuum an area of floor in an office or in your work vehicle as appropriate)?

2. p.t.o

Study dates/ timing

Collection of the duplicate diet requires you to keep a lidded bucket with you for the day, which could be potentially problematic if you usually cycle, walk or take public transport to work. Ideally you should come to Newcastle RVI the day immediately after collecting your diet sample, to provide your blood sample, this would need to be a week day (i.e. Mon-Fri).

1. Do you have a preferred week/s to undertake the study

3. And/ or a preferred day for collecting the duplicate diet sample?

4. Do you have any holidays/extended trips planned during the next 4 months and if so when?

5. Are there dates when you would definitely not be able to undertake the study?

6. Are you happy to give a blood sample, not afraid of needles, and able to attend the RVI one morning to provide the blood sample?

7. Are you happy to allow the researcher to collect a dust sample from your main living area and bedroom (vacuum an area of floor/sofa/ bed/pillow)?

Flame Retardants: Exposure and Body Burden Study **Participant …… Daily checklist**

Day …….. **Date**…….. **Time of visit** ……	**Day 0** **(approx 1 hr in evening)**	Lindsay will come to your home to bring the lifestyle and food frequency questionnaire, complete room contents survey, duplicate diet collection equipment and give instructions for completion of the activity and food diary and duplicate diet
Day …….. **Date**……..	**Day 1** **(approx 1 hr in evening)**	Please complete your activity and food diary throughout the day and complete the lifestyle and food frequency questionnaire
Day …….. **Date**……..	**Day 2** **(approx 15 mins total)**	Please complete your activity and food diary throughout the day
Day …….. **Date**……..	**Day 3** **(approx 15 mins)**	Please complete your activity and food diary throughout the day**.**
Day …….. **Date**……..	**Day 4** **(approx 15 + 30 mins)**	Please complete your activity and food diary throughout the day If possible Lindsay may visit your workplace to take a dust sample.
Day …….. **Date**……..	**Day 5** **(approx 15 mins total)**	Please complete your activity and food diary throughout the day
Day …….. **Date**……..	**Day 6** **(approx 15 mins total)**	Please complete your activity and food diary throughout the day
Day …….. **Date**…….. **Time of LBs visit** … ……	**Day 7** **(approx 15 + 15 + 45 mins)**	Please complete your activity and food diary throughout the day **and collect your duplicate diet sample.** Lindsay will visit you at home to collect a dust sample from your main living area, bedroom and vehicle if appropriate, the duplicate diet samples, breast milk sample if appropriate, questionnaire, room contents survey and activity and food diary. Please **do not snack after your evening meal**
Day …….. **Date**…….. **Time of CRF appt**… ……	**Day 8** **(approx 1hr in morning)**	Please attend your morning appointment at the CRF in the RVI for some simple measurements, blood sample collection and **collection of your shopping voucher. Remember to take directions and wear suitable clothing.**

Instructions for the completion of the room survey.
Please complete this for the two/three rooms you spend most time in during an average 24 hour period.

If you spend a lot of time in a vehicle such as a car, bus, lorry, train or aeroplane please record the vehicle type, make, model and country of origin where known, age, and time spent in the vehicle during a normal 24 hour period. (see questionnaire Transportation section)

Delete home or workplace as appropriate

Complete the following:
Room name:
e.g. office, shop, kitchen, living room, bedroom,

Air treatment:
e.g. humidifier, air filter, a special vacuum cleaner or special household products to help control allergies

Room ventilation:
e.g. window, fan, air conditioner

Frequency of dusting:
e.g. <once per month, < once per week but > once per month, <once per day but > once per week, once or more each day

Type of flooring
e.g. wood, laminate, carpet, linoleum/vinyl,

Age of flooring
e.g. >50yrs, 20-50 yrs, 10-20 yrs, 3-10 yrs, 3yrs to 6 months, >6 months.

Floor cleaning methods and frequencies:
e.g. Vacuum, sweeping, washing
e.g. <once per month, < once per week but > once per month, <once per day but > once per week, once or more each day

Is your vacuum in good working order?
Yes / no / don't know

Soft furnishings
Items:
e.g. settee, armchair, curtains, pouf, rug, bean bag, scatter cushions(Note foam or down), dining chair seats, mattress (Note foam or sprung), bed headboard, pillows (Note foam or down), office chair.

Age of soft furnishing item
e.g. >50yrs, 20-50 yrs, 10-20 yrs, 3-10 yrs, 3yrs to 6 months, >6 months, unknown.

Country of soft furnishing manufacture/origin:
e.g. UK, China, unknown

Time in this room:
e.g. >50yrs, 20-50 yrs, 10-20 yrs, 3-10 yrs, 3yrs to 6 months, >6 months

Soft furnishing usage per day (your personal usage) :
e.g. < 30 mins, 30 mins- 1 hour, 1-2 hours, 2-4 hours, 4-12 hours

Electronic items:
e.g. computer, TV, DVD player, video recorder, freeview box, HiFi components, speakers, radio, games consoles, gameboy, keyboard, toys,mobile phone, mobile phone charger, home phone, radio alarm clock, heated curlers, hairdryer, straightening tongs, electric heater, electric blanket, printer, photocopier, cash register, vacuum, floor polisher, coffee machine, microwave,

Age of electronic item:
e.g.>20 years, 10-20 yrs, 3-10 yrs, 3yrs to 6 months, >6 months, unknown

Country of electronic item manufacture/origin:
e.g. UK, China, unknown

Make/model of electronic item:
This will help us identify the age and country of origin if you do not know them.
e.g. Sony Ericsson W980, unknown

Time in this room:
e.g. >20yrs, 10-20 yrs, 3-10 yrs, 3yrs to 6 months, >6 months,
*this item moves around the house

Time switched on (e.g. on standby)
e.g. <15 mins, 15- 30 mins, 30 mins- 1 hour, 1-2 hours, 2-4 hours, 4-12 hours

Usage per day (your personal usage) :
e.g. <15 mins, 15- 30 mins, 30 mins- 1 hour, 1-2 hours, 2-4 hours, 4-12 hours

Participant ID:			Home / workplace (delete as appropriate)			Room name:			Date of survey:		
Air treatment:			Room ventilation:			Frequency of dusting:					
						Floor cleaning methods and frequencies:					
Flooring type:			Flooring age:								
						Is your vacuum in good working order?					

Soft furnishings					Electronic items						
item	age	country of origin	time in room	time used by you per day	item	age	country of origin	make and model	time in room	time used by you per day	time switched on per day

In the past two years, have you had any furniture in your house or workplace that had exposed or crumbling foam? Y / N

How to sample dust from the living room floor

1. In the plastic bag you will find: A twist tie and a sample 'sock' for dust collection. Please keep the bag closed until sampling and minimise touching the socks.

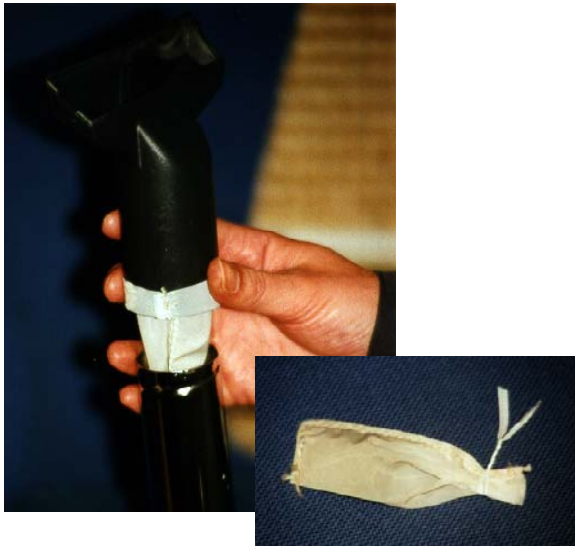
2. Use the 'sock' marked 'living room floor' (or ‘rug’; see below). Slide the opening of the 'sock' over the furniture attachment (small vacuum foot) of the vacuum cleaner.

3. Trap the 'sock' firmly into place. The 'sock' should always overlap onto the attachment.

4. Measure out a square of **1 m²** in (or close to) the **sitting area** on *carpeted floor*. In case of *bare smooth floor* sample **4 m²**. Mark the corners of the measured square meter(s). Small pieces of furniture may be moved, but do not move large objects such as sofas, book cases etc.

5 wall-to-wall carpet

5. Vacuum the square (**1 m²** in case of **wall to wall carpet** and **4 m²** in case of **bare smooth floors**) evenly and thoroughly for exactly **2 minutes (**or **4 minutes** in case of **smooth floor)**. The dust will collect inside the 'sock'. TURN THE FOOT UP AND THEN SWITCH OFF THE VACUUM CLEANER (to avoid dust falling out).



6. Carefully remove the 'sock'. Tie the top with the twist tie. Place the 'sock' into the plastic bag and close it tightly. Complete the information questionnaire, and return as advised.

Duplicate Diet Collection

Please place exactly the same amount of food that you eat in the bucket.

It is not necessary to place water in the bucket.

e.g. if drinking a cup of tea only put the milk and sugar in the bucket
if drinking coffee place only coffee granules (if instant) sugar and milk in the bucket
(no tea bags or coffee grounds thank-you)

If you cut fat of you meat e.g. a chop or bacon please remember to remove the fat from the portion for you bucket

If you are eating spare ribs or a chop please remember to remove the bone from the portion for your bucket

If you have a hardboiled egg, remember to remove the shell.

Leave out the crusts of toast or sandwiches if you do not eat them.
Remember to spread butter, margarine, jam, marmite or peanut butter if you use them.

If you are eating fruit remember to prepare the sample for your bucket as you would for eating, e.g., remove apple core and peel, remove banana peel, remove orange peel, wash grapes, remove strawberry leaves.

If you eat sweets remember to remove the wrapper

If you eat yoghurt please pour I out of the pot

When you are eating dinner remember to include and sauces such as mayonnaise or ketchup, salad dressings or additional butter.

I find it easiest to prepare two identical plates of food, eat mine then add the 2nd to the bucket.

Thank-you!
Bon Appetit!

PLEASE REMEMBER TO:-

1. Carry this booklet with you everywhere for the week.

2. Write down where you are and what you are doing

3. Write down everything that you eat or drink but don't include any leftovers.

4. Write down how much you eat or drink, for example,
   - Drinks – as glasses, cups or mugs, cans, cartons or bottles
   - Cereal – tablespoons or bowls.
   - Jam or sugar – teaspoons or tablespoons

5. Don't forget sweets and snacks, even small amounts are important.

Flame Retardants: Exposure and Body Burden Study (FREBB)

Food and Activity Diary

For office use only

Participant ID:

Examples of how to fill in the record sheet

Day:……Monday**……**

Date……23rd April**……**

Time	Food or drink	Amount eaten	Food atlas code
7.30 am	ASDA Cornflakes	1 bowl	55
7.30 am	Full cream milk	1/2 cup	110ml
7.30 am	White sugar	1 tsp	
10.30 am	Mars bar	1 normal size	
10.30 am	bottle sprite	½ 330ml bottle	
12.30pm	Wholemeal bread	2 slim slices	2 x L (G1)
12.30pm	Flora margarine	Spread on bread	301
12.30pm	Emmental cheese	Sandwich filling	244
12.30pm	Plum chutney	1 dessert spoon	10 ml
12.30pm	bottle sprite	½ 330ml bottle	

Continue for the rest of the day; carry on to new sheet where necessary. Always start a new day on a new sheet. You will be given a copy of the Food Atlas to help you describe amounts of food or drink consumed.

Day:…… Monday……

Date…….23rd April**……**

Time	Venue	Activity
8.00 – 8.30	car	Drive to work
9.00 – 17.00	Work, office	At computer, 5 mins printing and photocopying
17.30 – 18.00	Car	Drive home
18.00 – 19.30	garden	
19.30 – 20.00	kitchen	Listened to radio, Prepared dinner, cooked using oven, ironed, washed up,
20.00 – 22.00	Living room	Eat dinner sitting on settee, watch TV (1 hr) Play on games console (1 hr)
22.30 – 07.00	Bedroom	

Flame Retardants: Exposure and Body Burden Study

Exposure Assessment Questionnaire

Instructions

Before we start, let me tell you a few things about the survey.

This will take about 90 minutes. All of the answers you give us are completely confidential. No one except the study team will see your name or contact information.

Your participation in this survey is voluntary. If you feel uncomfortable answering a question, just let me know, and we'll skip that one. There are no right or wrong answers here – it's just important that you answer the questions as accurately as you can. If you don't understand the question, let me know, and I'll repeat it.

When we're finished, I'll give you some information on sample collection.

Do you have any questions for me?

Participant Identification #:

_____

Enter this number on Page 2

Contact Information Sheet

We are asking for your personal contact information only for the purpose of:

- Contacting you to arrange times for sample collection
- Contacting you with a newsletter with findings of the study
- Contacting you regarding further research if you have ticked this box on the consent form

This form will be separated from the questionnaire and kept in a locked file cabinet and/or on a password protected computer. A code number will be used to identify the questionnaire and your sample. Only Lindsay and Tanja will have access to the file linking your code number to your contact information.

Telephone Number:
Please indicate whether this is work, home or mobile and when would the best time to call you

Address:

Email:

Participant Identification #:

_____

General Health/Personal Characteristics

These are just a few general questions about your personal characteristics and overall health.

In what year were you born? (MUST BE PRE 1992 IN ORDER TO BE ELIGIBLE)

Are you male or female?

How would you rate your general health? Excellent / Very good / Good / Fair / Poor

Were you breast fed as a baby? Yes/No

If yes do you know how long for? 0-2 months / 2-6 months / 6+ months

Do you have allergies or asthma?

If yes can you give a little more detail please_____

Within the last three years, have you ever regularly smoked cigarettes / cigars / a pipe?

If yes which?

Have you stopped smoking?

If you have stopped smoking how many years ago did you stop?

On average, how many cigarettes/ cigars/ pipes did you smoke each day before you stopped?

For how many years did you smoke before you stopped?

Do you currently live with a smoker?

How many hours per day are you at home with a smoker?

Does this person smoke inside the house?

Do you have any habits like biting your nails or sucking your thumb?

If yes can you give a little more detail please_____

Have you ever been in a house/ office/ car fire? When was this?
If yes can you give more detail please_____

Do you have pets (except birds or) fish that you keep in the home?

If so what kind of pets do you have? _____

Who else currently lives in your house (except you and your partner)?

Relationship to you						
Age						
Sex						

What is it like where you live? rural/ urban

Do you have any illnesses for which you are taking mediation?

To which of these groups do you consider you belong?

White |___| Indian |___| Pakistani |___|

Bangladeshi |___| Chinese |___| Black Caribbean |___|

Black –other |___| Describe_____

Other |___| Describe_____

How many children have you had? _____

Was/ were your child/children planned and if so how long did it take you and your partner to conceive? _____

If you do not have children is that by choice or nature?_____

For women only

How many children have you breastfed before?_____

How long did you breast feed each of these?_____

For breastfeeding mothers only

For how long have you been breastfeeding?_____

Occupational Exposure

I'm going to ask you a few questions about the types of jobs that you've had in the past three years, starting from your most recent job and working backwards in time. Please include any jobs that you've held for more than six months and that you worked at for more than 20 hours per week. What we're interested in is the type of work that you've done, not the name of the business.

Do you have a paid job at present?

If no how would you describe yourself?

Housewife/ husband	|___|	Retired	|___|
Unemployed	|___|	Student	|___|
Maternity leave	|___|	Other	|___|
		Describe _____	

When did you last work? _____

If it is more than 2 years since you were employed what did you used to do and for how long?

_____

Jobs held for a duration of > six months, within the past two years:			
For how long did you work at this job?			
What dates (approx) did you start and finish this job?			
What kind of work did you do there?			
How many hours a week did you work?			
Did this job sometimes involve the manufacturing or processing of fabrics, plastics, or foam? (Y / N)			
Did this job sometimes involve working on a computer or photocopier or was there such equipment in your office? (Y / N)			
Did this job involve working in a car, on a bus, train or aeroplane? (Y / N)			
Did you sit on a foam padded chair? (Y / N)			

Please list all other jobs you have done (we may contact you again for further information on these).

Hobbies/Crafts/Home Improvement

This section of questions is about hobbies, crafts, or work around the house that you might do when you're not at work.

Do you play with a game console?

Do you have any regular hobbies like arts and crafts or model building or do you do any home improvement work that involve working with plastic, foam, or fabric ?

If yes please specify. You may be asked for more detail about this

Please list your hobbies and pastimes past and present (we may contact you for further information about these)

Transportation

How frequently do you fly (approximate average flights per year)…

…Returns within Europe (short haul)?.....

…Returns beyond Europe (long haul)?.....

The next questions are questions about your vehicle or vehicles that you regularly ride in. By "regularly" we mean more than once per week on average

Do you regularly (once or more per week on average) take the bus, metro or train?

If you spend a lot of time in a vehicle such as a car, bus, lorry, train or aeroplane please record the vehicle type, make, model and country of origin where known, age, and time spent in the vehicle during a week. If you don't know all the details it's ok, the vehicle type and approximate hours spent in the vehicle in an average week are most important. There are enough tables for 3 vehicle types below.

vehicle type	
hours spent in vehicle in an average week	
make	
model	
country of manufacture	
Age of vehicle (approximate years)	
Does the vehicle have any exposed foam?	**Y / N / don't know**
Does the vehicle have air conditioning?	**Y / N / don't know**
How often are the windows opened?	**Everytime / sometimes / only in summer / rarely / never**
How often is the interior cleaned/ vacuumed?	**Once or more a week / every month / every 6 months / less often / never / don't know**

vehicle type	
hours spent in vehicle in an average week	
make	
model	
country of manufacture	
Age of vehicle (approximate years)	
Does the vehicle have any exposed foam?	**Y / N / don't know**
Does the vehicle have air conditioning?	**Y / N / don't know**
How often are the windows opened?	**Everytime / sometimes / only in summer / rarely / never**
How often is the interior cleaned/ vacuumed?	**Once or more a week / every month / every 6 months / less often / never / don't know**

vehicle type	
hours spent in vehicle in an average week	
make	
model	
country of manufacture	
Age of vehicle (approximate years)	
Does the vehicle have any exposed foam?	**Y / N / don't know**
Does the vehicle have air conditioning?	**Y / N / don't know**
How often are the windows opened?	**Everytime / sometimes / only in summer / rarely / never**
How often is the interior cleaned/ vacuumed?	**Once or more a week / every month / every 6 months / less often / never / don't know**

Food Frequency Questionnaire

This questionnaire asks for some background information about what you eat.

Do you eat any meat ? Y / N

If no, approximately how many years ago did you last eat meat?.....

Do you eat fish? Y / N

If no, approximately how many years ago did you last eat fish?.....

Do you eat any dairy products (including milk, cheese, butter, yoghurt)? Y / N

If no, approximately how many years ago did you last eat dairy products?.....

Do you eat eggs (including eggs in cakes and other baked foods)? Y / N

If no, approximately how many years ago did you last eat eggs?.....

Listed below are 130 food items divided into sections according to food type. For each food there is an amount shown, either a 'medium serving' or a common household unit such as a slice or teaspoon. Please put a cross 'x' in the box to indicate how often, on average, you have eaten the specified amount of each food during the last 12 months.

Examples . 12-36 days a year would be 1-3 times per month

52 days would be once a week

EXAMPLES:

For the white bread the amount is one slice, so if you ate 4 or 5 slices a day, you should put a tick in the column headed "4-5 per day".

FOODS AND AMOUNTS	**AVERAGE USE LAST YEAR**								
BREAD AND SAVOURY BISCUITS (one slice or biscuit)	Never or less than once/month	1-3 per month	Once a week	2-4 per week	5-6 per week	Once a day	2-3 per day	4-5 per day	6+ per day
White bread and rolls								*X*	

For chips, the amount is a "medium serving", so if you had a helping of chips twice a week you should put a tick in the column headed "2-4 per week".

FOODS AND AMOUNTS	**AVERAGE USE LAST YEAR**								
POTATOES, RICE AND PASTA (medium serving)	Never or less than once/month	1-3 per month	Once a week	2-4 per week	5-6 per week	Once a day	2-3 per day	4-5 per day	6+ per day
Chips				*X*					

For fruit the amount is one medium portion

FOODS AND AMOUNTS	**AVERAGE USE LAST YEAR**								
FRUIT (1 fruit or medium serving)	Never or less than once/month	1-3 per month	Once a week	2-4 per week	5-6 per week	Once a day	2-3 per day	4-5 per day	6+ per day
Strawberries, raspberries, kiwi fruit			*X*						

Please estimate your average food use as best as you can, and please answer every question - do not leave ANY lines blank. PLEASE PUT A TICK (X) ON EVERY LINE

FOODS AND AMOUNTS	**AVERAGE USE LAST YEAR**								
MEAT AND FISH (medium serving)	Never or less than once/month	1-3 per month	Once a week	2-4 per week	5-6 per week	Once a day	2-3 per day	4-5 per day	6+ per day
Beef: roast, steak, mince, stew or casserole									
Beefburgers									
Pork: roast, chops, stew or slices									
Lamb: roast, chops or stew									
Chicken or other poultry eg. Turkey									
Bacon									
Ham									
Corned beef, Spam, luncheon meats									
Sausages									
Savoury pies, e.g. meat pie, pork pie, pasties, steak & kidney pie, sausage rolls									
Liver, liver pate; liver sausage									
Fried fish in batter, as in fish and chips									
Fish fingers, fish cakes									
Other white fish, fresh or frozen, eg. cod, haddock, plaice, sole, halibut									
Oily fish, fresh or canned, eg. mackerel, kippers, tuna, salmon, sardines, herring, eel									
Shellfish, e.g. crab, prawns, mussels									
Fish roe, taramasalata									

Please check that you have a tick (X) on EVERY line

What did you do with the visible fat on your meat?

Ate most of the fat |___| Ate as little as possible |___|
Ate some of the fat |___| Did not eat meat |___|

How often did you eat grilled or roast meat? |___| times a week

How well cooked did you usually have grilled or roast meat?

Well done/dark brown |___| Lightly cooked/rare |___|
Medium |___| Did not eat meat |___|

PLEASE PUT A TICK (X) ON EVERY LINE

FOODS AND AMOUNTS	**AVERAGE USE LAST YEAR**								
BREAD AND SAVOURY BISCUITS (one slice or biscuit)	Never or less than once/month	1-3 per month	Once a week	2-4 per week	5-6 per week	Once a day	2-3 per day	4-5 per day	6+ per day
White bread and rolls									
Brown bread and rolls									
Wholemeal bread and rolls									
Cream crackers, cheese biscuits									
Crispbread, e.g. Ryvita									
CEREALS (one bowl)									
Porridge, Readybrek									
Breakfast cereal such as cornflakes, muesli etc.									

Please check that you have a tick (X) on EVERY line

PLEASE PUT A TICK (X) ON EVERY LINE

FOODS AND AMOUNTS	**AVERAGE USE LAST YEAR**								
BREAD AND SAVOURY BISCUITS (one slice or biscuit)	Never or less than once/month	1-3 per month	Once a week	2-4 per week	5-6 per week	Once a day	2-3 per day	4-5 per day	6+ per day
POTATOES, RICE AND PASTA (medium serving)									
Boiled, mashed, instant or jacket potatoes									
Chips									
Roast potatoes									
Potato salad									
White rice									
Brown rice									
White or green pasta, eg. spaghetti, macaroni, noodles									
Wholemeal pasta									
Lasagne, moussaka									
Pizza									

Please check that you have a tick (X) on EVERY line

PLEASE PUT A TICK (X) ON EVERY LINE

FOODS AND AMOUNTS	**AVERAGE USE LAST YEAR**								
DAIRY PRODUCTS AND FATS	Never or less than once/month	1-3 per month	Once a week	2-4 per week	5-6 per week	Once a day	2-3 per day	4-5 per day	6+ per day
Single or sour cream (tablespoon)									
Double or clotted cream (tablespoon)									
Low fat yogurt, fromage frais (125g carton)									
Full fat Greek yogurt (125g carton)									
Dairy deserts (125g carton)									
Cheese, e.g. Cheddar, Brie, Edam (medium serving)									
Cottage cheese, low fat soft cheese (medium serving)									
Eggs as boiled fried, scrambled, etc. (one)									
Quiche (medium serving)									
Low calorie, low fat salad cream (tablespoon)									
Salad cream, mayonnaise (tablespoon)									
French dressing (tablespoon)									
Other salad dressing (tablespoon)									
The following on bread or vegetables									
Butter (teaspoon)									
Block margarine, e.g. Stork, Krona (teaspoon)									
Polyunsaturated margarine (tub), e.g. Flora, sunflower (teaspoon)									
Other soft margarine, dairy spreads (tub), e.g. Blue Band, Clover (teaspoon)									
Low fat spread (tub), e.g. Outline, Gold (teaspoon)									
Very low fat spread (tub) (teaspoon)									

Please check that you have a tick (X) on EVERY line

PLEASE PUT A TICK (X) ON EVERY LINE

FOODS AND AMOUNTS	**AVERAGE USE LAST YEAR**								
SWEETS AND SNACKS (medium serving)	Never or less than once/month	1-3 per month	Once a week	2-4 per week	5-6 per week	Once a day	2-3 per day	4-5 per day	6+ per day
Sweet biscuits, chocolate, e.g. digestive (one)									
Sweet biscuits, plain, e.g. Nice, ginger (one)									
Cakes e.g. fruit, sponge, home baked									
Cakes e.g. fruit, sponge ready made									
Buns, pastries e.g. scones, flapjacks, home baked									
Buns, pastries e.g. croissants, doughnuts, ready made									
Fruit pies, tarts, crumbles, home baked									
Fruit pies, tarts, crumbles, ready made									
Sponge pudding, home baked									
Sponge pudding, ready made									
Milk puddings, e.g. rice, custard, trifle									
Ice cream, choc ices									
Chocolate, single or squares									
Chocolates, snack bars e.g. Mars, Crunchie									
Sweets, toffees, mints									
Sugar added to tea, coffee, cereal (teaspoon)									
Crips or other packet snacks , e.g. Wotsits									
Peanuts or other nuts									

Please check that you have a tick (X) on EVERY line

PLEASE PUT A TICK (X) ON EVERY LINE

FOODS AND AMOUNTS	**AVERAGE USE LAST YEAR**								
SWEETS AND SNACKS (medium serving)	Never or less than once/month	1-3 per month	Once a week	2-4 per week	5-6 per week	Once a day	2-3 per day	4-5 per day	6+ per day
SOUPS, SAUCES, AND SPREADS									
Vegetable soups (bowl)									
Meat soups (bowl)									
Sauces, e.g. white sauce, cheese sauce, gravy (tablespoon)									
Tomato ketchup (tablespoon)									
Pickles, chutney (tablespoon)									
Marmite, Bovril (teaspoon)									
Jam, marmalade, honey (teaspoon)									
Peanut butter (teaspoon)									

Please check that you have a tick (X) on EVERY line

PLEASE PUT A TICK (X) ON EVERY LINE

FOODS AND AMOUNTS	**AVERAGE USE LAST YEAR**								
DRINKS	Never or less than once/month	1-3 per month	Once a week	2-4 per week	5-6 per week	Once a day	2-3 per day	4-5 per day	6+ per day
Tea (cup)									
Coffee, instant or ground (cup)									
Coffee, decaffeinated (cup)									
Coffee whitener, e.g. Coffee-mate (teaspoon)									
Cocoa, hot chocolate (cup)									
Horlicks, Ovaltine (cup)									
Wine (glass)									
Beer, lager or cider (half pint)									
Port, sherry, vermouth, liqueurs (glass)									
Spirits, e.g. gin, brandy, whisky, vodka (single)									
Low calorie or diet fizzy soft drinks (glass)									
Fizzy soft drinks, e.g. Coca cola, lemonade (glass)									
Pure fruit juice (100 %) e.g. orange, apple juice (glass)									
Fruit squash or cordial (glass)									

Please check that you have a tick (X) on EVERY line

PLEASE PUT A TICK (X) ON EVERY LINE

FOODS AND AMOUNTS	**AVERAGE USE LAST YEAR**								
	Never or less than once/month	1-3 per month	Once a week	2-4 per week	5-6 per week	Once a day	2-3 per day	4-5 per day	6+ per day
SWEETS(medium serving)									
FRUIT									
Apples (1 fruit)									
Pears (1 fruit)									
Oranges, satsumas, mandarins (1 fruit)									
Grapefruit (half)									
Bananas (1 fruit)									
Grapes (medium serving)									
Melon (1 slice)									
*Peaches, plums, apricots (1 fruit)									
*Strawberries, raspberries, kiwi fruit (medium serving)									
Tinned fruit (medium serving)									
Dried fruit, e.g. raisins, prunes (medium serving)									

Please check that you have a tick (X) on EVERY line

FOODS AND AMOUNTS	**AVERAGE USE LAST YEAR**								
VEGETABLES Fresh, frozen or tinned (medium serving)	Never or less than once/month	1-3 per month	Once a week	2-4 per week	5-6 per week	Once a day	2-3 per day	4-5 per day	6+ per day
Carrots									
Spinach									
Broccoli, spring greens, kale									
Brussels sprouts									
Cabbage									
Peas									
Green beans, broad beans, runner beans									
Marrow, courgettes									
Cauliflower									
Parsnips, turnips, swedes									
Leeks									
Onions									
Garlic									
Mushrooms									
Sweet peppers									
Beansprouts									
Green salad, lettuce, cucumber, celery									
Watercress									
Tomatoes									
Sweetcorn									
Beetroot									
Coleslaw									
Avocado									
Baked beans									
Dried lentils, beans, peas									
Tofu, soya meat, TVP, Veggie burger									

Please check that you have a tick (X) on EVERY line

2. Are there any **OTHER** foods which you ate more than once a week? Yes |___| No |___|
If yes, please list below

Food	Usual serving size	Number of times eaten each week

3. What type of milk did you most often use?
Select one only Full cream, silver |___| Semi-skimmed, red/white |___|
Skimmed/blue |___| Channel Islands, gold |___|
Dried milk |___| Soya |___|
Other, *specify* |_____| None |___|

4. How much milk did you drink each day, including milk with tea, coffee, cereals, etc?
None |___| Three quarters of a pint |___|
Quarter of a pint |___| One pint |___|
Half a pint |___| More than one pint |___|

5. Did you usually eat breakfast cereal (excluding porridge and Ready Brek mentioned earlier)?
Yes |___| No|___|
If yes, which brand and type of breakfast cereal, including muesli, did you usually eat?
List the one or two types most often used

Brand *e.g. Kellogg's*	Type *e.g. cornflakes*

6. What kind of fat did you most often use for frying, roasting, grilling etc?
Select one only Butter |___| Solid vegetable fat |___|
Lard/dripping |___| Margarine |___|
Vegetable oil |___| None |___|

If you used vegetable oil, please give type eg. corn, sunflower |_____|

What kind of fat did you most often use for baking cakes ect?
Select one only Butter |___| Solid vegetable fat |___|
Lard/dripping |___| Margarine |___|
Vegetable oil |___| None |___|

If you used margarine, please give name or type eg. Flora, Stork _____|

8. How often did you eat food that was fried at home?

Daily |___| 1-3 times a week |___| 4-6 times a week |___|
Less than once a week |___| Never |___|

9. How often did you eat fried food away from home?

Daily |___| 1-3 times a week |___| 4-6 times a week |___|
Less than once a week |___| Never |___|

10. Have you taken any vitamins, minerals, fish oils, fibre or other food supplements during the past year? Yes |___| No |___| Don't know |___|

If yes, list brand and daily dose

11. In the last 12 months have you eaten a modified diet for any of these reasons?
Tick more than one if applicable

High blood pressure |___|
Stomach problems (e.g. ulcer or gastritis) |___|
Bowel problems (e.g. irritable bowel or diverticulitis |___|
Allergies (e.g. skin rash) |___|
Concern over a family history of illness |___|
High blood cholesterol |___|
Overweight/ obesity |___|
Diabetes |___|
Concern over eating a healthy diet |___|
Not modified my diet |___|
Other |___| Specify _____

Thank you for your help

Appendix D

Presentations given on studies outside this thesis but undertaken concurrently and selected supporting abstracts and posters

1. Table of presentations

2. 2008, International Society of Environmental Epidemiology and International Society of Exposure Assessment Joint Annual Conference, Pasadena, USA. Oral presentation *'Health Risk Assessment of Urban Agriculture Sites Using Vegetable Uptake and Bioaccessibility Data - an Overview of 28 Sites with a Combined Area of 48 Hectares*' ***– abstract***

3. 2008, International Society of Environmental Epidemiology and International Society of Exposure Assessment Joint Annual Conference, Pasadena, USA, poster presentation *'Case Study of Public Health Intervention at an Urban Agriculture Site in Newcastle-Upon-Tyne, UK'*- ***abstract***

4. 2010, 5th International Symposium on Brominated Flame Retardants, BFR2010, Kyoto, Japan, poster presentation' *The 'Tyne Fish Project' – Including concentrations of BFRs and congener profiles in different fish species and sample types from the Tyne River estuary*-***poster***

5. 2011, Persistent Organic Pollutants Network Conference, Birmingham, UK, poster presentation *'The Tyne Fish Project*'-**poster**

6. 2015, Institute for Sustainability Annual Conference, Newcastle University, poster presentation *Newcastle Allotments Biomonitoring Study (NABS)*-***poster***

7. 2016, 32nd Society of Environmental Geology and Health (SEGH), Brussels, oral presentation *'Newcastle Allotments Lead Biomonitoring Study: an investigation into the relationship between allotment soil lead concentrations and the blood lead concentration of gardeners*' ***–abstract***

8. 2016, 32nd Society of Environmental Geology and Health (SEGH), Brussels, poster presentation. '*Newcastle Allotments Lead Biomonitoring Study: an investigation into the relationship between the blood lead concentration of gardeners and the solid phase partitioning and bioaccessibility of soil lead'*-***poster***

Year	Presentation
2008*	**International Society of Environmental Epidemiology and International Society of Exposure Assessment Joint Annual Conference, Pasadena, USA. Over 1,000 delegates, academia and government regulators. Oral presentation 'Health Risk Assessment of Urban Agriculture Sites Using Vegetable Uptake and Bioaccessibility Data - an Overview of 28 Sites with a Combined Area of 48 Hectares' and poster presentation 'Case Study of Public Health Intervention at an Urban Agriculture Site in Newcastle-Upon-Tyne, UK'**
2010*	5th International Symposium on Brominated Flame Retardants in Kyoto, Japan, poster presentation' The 'Tyne Fish Project' – Including concentrations of BFRs and congener profiles in different fish species and sample types from the Tyne River estuary
2010	Institute of Health and Society, Newcastle, UK, Research Day, poster presentation 'The Tyne Fish Project'
2010	Persistent Organic Pollutants Network Conference, UK based meeting with some international plenary speakers, approximately 120 delegates from academia, regulators and industry, poster presentation 'The Tyne Fish Project'.
2010	**Sediments Workshop, Newcastle University, approximately 100 participants, invited speaker on 'The Tyne Fish Project'.**
2011*	Persistent Organic Pollutants Network Conference, UK based meeting with some international speakers, approximately 120 delegates from academia, regulators and industry poster presentation 'The Tyne Fish Project'.
2012	**Biomarkers Meeting, Newcastle University, approximately 30 participants invited from UK academia, regulators and industry, invited speaker on 'Biomarkers as evidence of Environmental Contamination'.**
2015*	Institute for Sustainability Annual Conference, Newcastle University, poster presentation Newcastle Allotments Biomonitoring Study (NABS)
2015	Newcastle Research in Sustainability Conference (RISe) 2015, poster presentation 'NABS' prize winning poster
2016	**Newcastle Allotments Biomonitoring Study (NABS) Public Engagement Event, informal celebration, thank you and talks to provide initial findings of the NABS study to participants, funders and stakeholders.**
2016	UK and Ireland Exposure Science and Occupational Epidemiology Meeting, Buxton, approx. 120 delegates from academia, industry and regulation oral presentation 'Newcastle Allotments Biomonitoring Study'
2016	**Joint Northern Contaminated Land Fora Annual Conference, Teesside, UK approximately 150 delegates, industry and regulators invited oral presentation, 'Newcastle Allotments Biomonitoring Study'.**
2016*	32nd Society of Environmental Geology and Health (SEGH), Brussels, 250 delegates mostly academics, oral presentation 'Newcastle Allotments Lead Biomonitoring Study: an investigation into the relationship between allotment soil lead concentrations and the blood lead concentration of gardeners' and poster presentation Newcastle Allotments Lead Biomonitoring Study: an investigation into the relationship between the blood lead concentration of gardeners and the solid phase partitioning and bioaccessibility of soil lead.
2016	**Society of Brownfield Risk Assessment, Annual Christmas Conference, 120 delegates, industry and regulators, invited speaker, NABS.**
2017	**Biomonitoring Urban Gardening (BUG) Public Engagement Event, invited speaker, NABS.**

Notes. *abstract or poster presented in Appendix D

Abstract # 874

Health Risk Assessment of Urban Agriculture Sites Using Vegetable Uptake and Bioaccessibility Data - an Overview of 28 Sites with a Combined Area of 48 Hectares

Bramwell L,* Pless-Mulloli T,* Hartley P† **Institute of Health and Society, Newcastle University, Newcastle-upon-Tyne, United Kingdom; and †Regulatory Services and Public Protection, Newcastle City Council, Newcastle-upon-Tyne, United Kingdom.*

Background: Newcastle-upon-Tyne (population 260,000) is the regional capital of NE England (population 2,500,000) with a rich industrial and mining history stretching back as far as Roman times. Since the industrial revolution Urban Agriculture Sites (UAS) (known in the UK as Allotment Gardens) developed as part of the extension of urban areas reflecting the desire to retain non commercial agriculture. In 2004 we reported that 'allotment sites in previously industrial urban areas are of potential concern for local authorities because of the tension between supporting allotment gardening as a health promoting activity within deprived areas and protecting public health from exposure to contaminated land and produce.' In a previous study into effects of ash from an Energy from Waste plant used on paths on UAS (n=32) we found many sites had soil concentrations of lead and arsenic above UK Soil Guideline Values (SGVs). In 2004 we reported that 'UK CLEA guidance was weak in guiding decisions for allotments exceeding SGVs and that surveys of consumption habits of allotment gardeners are required as are health and bioaccessibility studies of heavy metals under UK conditions'.

Methods: An award from the UK's Department for the Environment, Farming and Rural Affairs (DEFRA) provided funding to investigate 28 sites listed by the previous reports, with contaminant concentrations above UK and European SGVs. Sites were investigated in accordance with standard UK guidance. Conceptual Exposure Models (CEMs) were developed for each site to determine possible sources, pathways and receptors of contaminants. Detailed Quantitative Risk Assessments (DQRA) were carried out on 12 of these sites including sampling and analysis of vegetable uptake of contaminants and bioaccessibility by Physiologically Based Extraction Test (PBET).

Results: From 400+ soil samples lead and arsenic were the two contaminants repeatedly found across the city: lead min = 210, median = 545, US95 = 684, max = 1315, arsenic min = 7, median = 22, US95 = 27, max = 45 all in mg/kg. Local coal contains lead and arsenic. Gardeners have historically used coal fire ash as a soil conditioner to help break up the heavy clay soils. Sites on or near coal mining sites were also found to have higher lead and arsenic. More recently established UASs do not have the raised lead and arsenic concentrations as coal fires were phased out of the city in the 1960s to improve air quality and health. Three sites were legally determined as contaminated land and underwent remediation. The evidence of low vegetable uptake and bioaccessibility of the contaminants led to the decision that all the other sites investigated were suitable for food production.

Conclusion: We present novel approaches to balancing health benefits of urban agriculture as part of sustainable urban development for an area with previous industrial history avoiding closure due to over cautious risk assessment.

Abstract # 1010

Case Study of Public Health Intervention at an Urban Agriculture Site in Newcastle-Upon-Tyne, UK

Hartley P,* Bramwell L,† Pless-Mulloli T† **Regulatory Services and Public Protection, Newcastle City Council, Newcastle-upon-Tyne, United Kingdom; and †Institute of Health and Society, Newcastle University, Newcastle-upon-Tyne, United Kingdom.*

Background: Initially investigated as a control in the context of another study this urban agriculture site was found to have concentrations of lead and arsenic well in excess of UK Soil Guideline Values (SGVs). This led it to be prioritised for further investigation, results of which we are presenting here.
Methods: A desk study and interviews were followed by development of a conceptual site model identifying potential contaminant sources, pathways and receptors. A sampling plan was created using the SPLUS environmental statistical package and subsequently intrusive soil sampling and collection of winter vegetable samples was undertaken. A second tier of sampling was undertaken to investigate the bioaccessibility (by Physiology Based Extraction Technique (PBET)) of lead and arsenic in the soil, lead in tap water at the site and lead and arsenic in summer vegetables at the site.
Results: The desk study revealed a colliery site and saw mill, which existed from 1836 until 1860, immediately to the northern boundary of the site and Victorian terraced housing to the east. The northern section of the site was an infilled stream valley with high groundwater levels and occasional flooding. Interviews and site walk-over revealed extensive historic usage of coal fire ash as a soil conditioner and lead pipework used for water distribution at the site. Initial soil sampling again indicated concentrations of lead (min = 620, median = 1100, US95 = 1315, max = 2000 all mg/kg) and arsenic (min = 20, median = 23, US95 = 25, max = 32 all mg/kg) above UK SGVs. Concentrations of lead and arsenic in winter vegetables indicated negligible uptake. Bioaccessibility results were low as would be expected for aged contamination. However, analysis of tap water indicated concentrations of lead of up to a hundred times the value prescribed in UK water supply regulations. Summer vegetables watered with tap water were found to have higher concentrations of lead than the winter vegetables but still well within the UK contaminants in food regulations safe concentrations. Analysis of groundwater showed no significant contamination.
Discussion: The results indicated that tap water from the lead pipes could pose a significant possibility of significant harm if used as drinking water but not if used only for watering vegetables. An incident group with members from the local government, health authorities and Newcastle University was convened to discuss the way forward. Risk from soil at the site was considered to be manageable by public health and personal hygiene methods. As the site was not owned by the local authority no funds were available for the replacement of lead pipes and as such plot holders have been strongly advised not to drink water from taps at the site and adopt a range of public health measures to reduce possible intake via potential soil ingestion pathways.

Institute of Health&Society

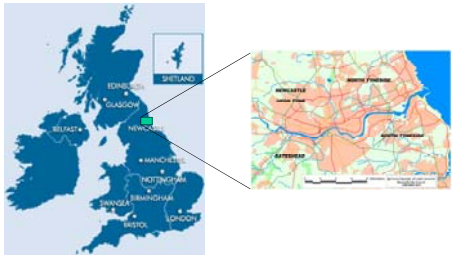
The Tyne Fish Project

Lindsay Bramwell[1,2] email: lindsay.bramwell@ncl.ac.uk
David Mortimer[3] Alwyn Fernandes[4] Martin Rose[4] Phil Hartley[2] Tanja Pless-Mulloli[1]
1.Newcastle University 2.Newcastle City Council
3.Food Standards Agency 4.Food and Environment Research Agency UK

Introduction

The River Tyne estuary is located in a densely populated conurbation of around a million people on both sides of the river banks. The area has a long industrial heritage and contaminated areas on both shores have been the subject of specific investigations and remediation. A substantial amount of angling takes place on the Tyne estuary and Newcastle City Council (NCC) is concerned about possible health impacts of entry into the food pathway of contamination of the river.

The Food Standards Agency (FSA) provided the Local Authority, NCC, with a grant towards the analysis of fish caught in the Tyne estuary.



Aim

To determine the concentrations of a range of contaminants in different fish species and sample types from the Tyne Estuary and to develop daily intake estimates associated with consumption of the fish to assess potential health risk.

Methods

A Project steering group was brought together to ensure all stakeholder needs are met and maximise value for money regarding integration with other Tyne projects. Members include local authorities, Health protection Agency, Food Standards Agency, Environment Agency, Natural England and the Tyne Rivers Trust.

NCC and Newcastle University are collecting fish and shellfish samples and information on local angling activities. Laboratory analysis is being carried out by Fera.

Muscle for each fish species and cod liver is being analysed for a range of contaminants.

Concentrations of PBDEs and HBCDs in fish muscle and liver and shellfish caught in the Tyne estuary are compared with similar studies from around the world.

Dietary intake of the BFRs for those consuming the Tyne fish are estimated and compared with national intake estimates.

Results

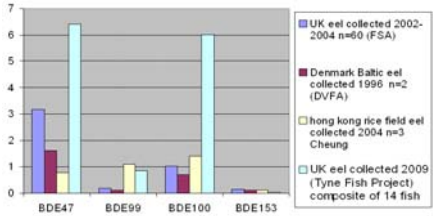
Concentrations of total PBDEs (ex BDE209) in cod caught in the Tyne estuary were found to be 3.8 times higher than concentrations reported in the FSAs UK fish study. Whiting loadings were 5 times higher. Tyne Flounder concentrations were similar to those measured in the UK Nith estuary[10] and 18 times less than those from the UK Tees estuary[10].

UK cod muscle (FSA) [5] vs Belgium cod muscle[6] $\sum PBDE_9$ = 0.22 ng/g vs 0.04 ng/g and $\sum HBCD$ (FSA)[5]= 0.34 ng/g[5]

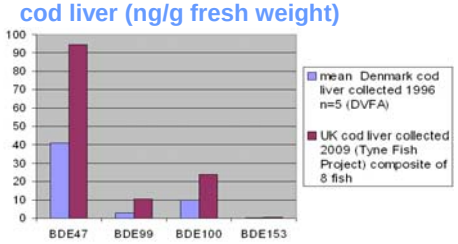
Danish cod liver[7] vs Tyne cod liver $\sum PBDE_4$ = 55 ng/g vs 129 ng/g

UK whiting muscle (FSA)[5] vs Tyne whiting muscle $\sum PBDE_{10}$ = 0.13 ng/g vs 0.65 ng/g, $\sum HBCD$ (FSA)[5]= 0.34 ng/g[5]

Distribution of PBDE congeners in eel muscle (ng/g fresh weight)



Distribution of PBDE congeners in cod liver (ng/g fresh weight)



Discussion

Reported national averages for daily fish consumption range from 31g for the UK[8] to 97g for Japan[9].

BDE47 is the PBDE congener commonly found at the highest concentrations.

α HBCD is the enantiomer found at the highest concentrations.

The RIVM recommended maximum daily intake for BDE99 of 0.23 -0.30 ng/kg bw/day has been used to calculate safe diet advice.

Comparison of data from previous studies is problematic due to:

- Different congeners analysed
- Different analytical methods used
- Different limits of detection
- Treatment of non detects
- Reporting of individual congeners vs sum of congeners
- Reporting of data range, mean or median
- Reporting as daily intake per person or as per kg body weight

Advice to Anglers

Assuming fish contributes 50% of the BDE99 intake from diet and diet contributes 50% of the total BDE 99 intake a 65 kg adult can eat one of the following each week:

unlimited cod or 250g (1.5 portions) whiting or
200g (1.25 portions) flounder or 80g (0.5 portion) eel or
6g cod liver

N.B. This advice is purely with respect to BDE99 – actual advice takes many other contaminants into consideration.

References

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The Tyne Fish Project

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Introduction

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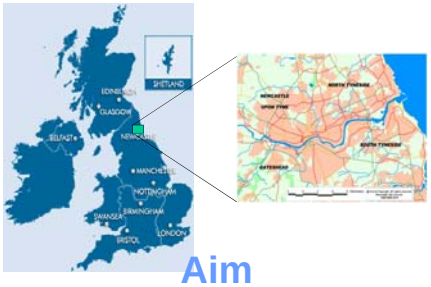

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To determine the concentrations of a range of contaminants in different fish species and sample types from the Tyne Estuary and to develop daily intake estimates associated with consumption of the fish to assess potential health risk.

Methods

A Project steering group was brought together to ensure all stakeholder needs were met and to maximise value for money regarding integration with other Tyne projects. Members included local authorities, Health protection Agency, Food Standards Agency, Environment Agency, Natural England and the Tyne Rivers Trust.

NCC and Newcastle University are collected fish and shellfish samples and information on local angling activities. Laboratory analysis was being carried out by Fera.

Muscle for each fish species and cod liver was being analysed for a range of contaminants.

Concentrations of dioxins and dioxin like PCBs, PBDEs and HBCDs in fish muscle and liver caught in the Tyne estuary were compared with similar studies from around the world.

Dietary intake of dioxins and dioxin like PCBs for those consuming Tyne fish were estimated and compared with national intake estimates.

Results

Concentrations of total dioxins and dioxin like PCBs in muscle of cod caught in the Tyne estuary were found to be approximately twice the concentration reported for cod sampled from UK retail outlets reported in 2006[1]. Tyne whiting muscle loadings were 1.6 those from the previous UK study[1]. Tyne eel muscle concentrations were three time those of the previous UK study[1]. Further comparisons can be seen in Table 1.

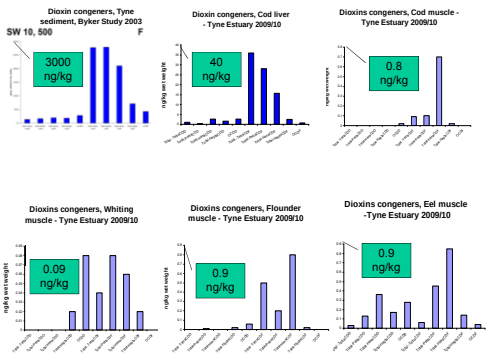
Concentrations of total PBDEs (ex BDE209) in cod caught in the Tyne estuary were found to be 3.8 times higher than concentrations reported in the FSAs UK fish study. Whiting loadings were 5 times higher. Tyne Flounder concentrations were similar to those measured in the UK Nith estuary[2] and 18 times less than those from the UK Tees estuary[2].

Danish cod liver[5] vs Tyne cod liver $\sum PBDE_4$ = 55 ng/g vs 129 ng/g

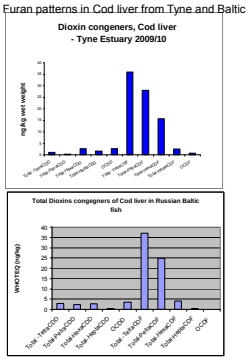
UK whiting muscle (FSA)[3] vs Tyne whiting muscle $\sum PBDE_{10}$ = 0.13 ng/g vs 0.65 ng/g, ∑HBCD (FSA)[5]= 0.34 ng/g[5]

Table 1. Sample Details

		Sum ng/kg wet weight WHO TEQ PCCD/F	Sum ng/kg wet weight WHO TEQ DLPCBs	Sum ng/kg wet weight WHO TEQ PCDD/F and DLPCBs
Whiting muscle	TFP 2009/10	0.06	0.09	0.15
	UK (2009)[6]	0.04	0.05	0.09
Flounder muscle	TFP 2009/10	0.14	0.14	0.28
	Baltic (2006)[7]	1.61	3.125	4.74
	South Korea (2004)[8]	0.38		
Eel muscle	TFP 2009/10	0.51	3.2	3.71
	UK (2009)[6]	0.38	0.93	1.3
	Amsterdam (1996)[9]	0.29		
Cod muscle	TFP 2009/10	0.05	0.12	0.17
	UK (2009)[6]	0.03	0.07	0.09
	Baltic (2009)[10]		0.21	
Cod liver	TFP 2009/10	9.86	41.6	51.46



Furan patterns in Cod liver from Tyne and Baltic



Discussion

Reported national averages for daily fish consumption vary widely, for example 31g for the UK[5] and 97g for Japan[5].

2,3,7,8, TCDF is the PCDD/F congener commonly found at the highest concentrations in Tyne fish (flounder, cod muscle and cod liver), OCDD for whiting and 1,2,3,4,7,8,HxCDF for eel.

PCB 153 is the congener found at the highest concentrations for all Tyne fish species and sample types.

BDE47 is the PBDE congener commonly found at the highest concentrations.

α HBCD is the enantiomer found at the highest concentrations.

Comparison of data from previous studies is problematic due to:

- Different congeners analysed
- Different analytical methods used
- Different limits of detection
- Treatment of non detects
- Reporting of individual congeners vs sum of congeners
- Reporting of data range, mean or median
- Reporting as daily intake per person or as per kg body weight

Advice to Anglers

The UK Committee on Toxicology recommends a maximum TDI for mixtures of PCDD/F and Dioxin like PCBs of 2pg WHO-TEQ/kg bw/day for women of reproductive age and girls and 8pg WHO-TEQ/kg bw/day for women of post reproductive age, men and boys.

The Dutch National Institute for Public Health and the Environment (RIVM) recommended maximum daily intake for BDE99 of 0.23 -0.30 ng/kg bw/day has been used to calculate safe diet advice. We have assumed that fish contributes 50% of the BDE99 intake from diet and diet contributes 50% of the total BDE 99 intake for a 65 kg adult.

The results of this study indicate that women and girls of reproductive age should be advised not to consume Tyne eel, flounder or whiting more than once every two weeks and all persons should be recommended to consume Tyne cod liver only occasionally.

This advice is purely relates to dioxins, dioxin-like PCBs and BDE99 – final advice will take many other contaminants into consideration.

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Acknowledgements

The Food Standards Agency (FSA) provided the Local Authority, NCC, with a grant towards the analysis of fish caught in the Tyne estuary.

Newcastle Allotments Lead Biomonitoring Study

Lindsay.Bramwell@ncl.ac.uk[ab], J. Morton[c], J. Entwistle[d], P. Hartley[b], T. Pless-Mulloli, Newcastle University[a], Newcastle City Council[b], Health and Safety Laboratory[c], Northumbria University[d]

IfS and NISR Responsive Mode Project BH148732

Introduction

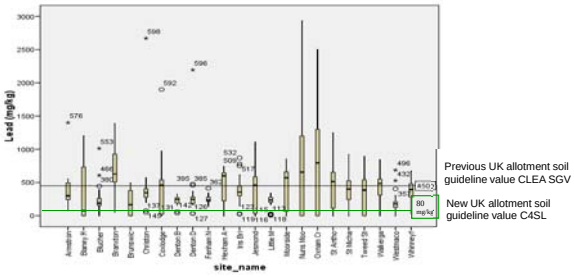
Allotment gardens are more than a source of fresh fruit and vegetables, they provide integration for communities, connection with nature, skills sharing, spirituality and therapy. An increasing number of young families can be found on allotments and waiting lists for plots are at an all-time high. Across Newcastle residential gardens and allotments frequently contain raised lead concentrations in soil. This is sometimes the result of previous industrial use, but also results from years of use of coal fire ash as soil improver (local coal contains lead) and ash from bonfires containing old window frames coated with lead paint (see Figure 1)[1]. Detailed quantitative risk assessments following the required UK procedures have been previously carried out on Newcastle's allotment gardens. Tests including plant uptake of lead and bioaccessibility of lead in soils indicated this soil lead to have low mobility[1.] NCC concluded that, on balance, gardening activities and consumption of vegetables from these sites is a greater benefit than risk to health.

Recent government recommendations for safe lead levels in allotment soil[2] are 10 times lower than those in Newcastle and many other urban areas in the UK and beyond. The aim of this study was to gather measured evidence on the relationship between concentrations of lead in garden soils and bloods.

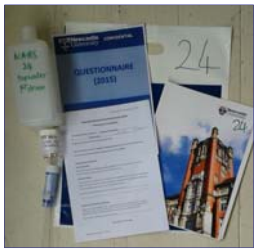
Methods

- A steering group including specialists from Public Health England (PHE), NCC, NU, Food Standards Agency (FSA), Environment Agency (EA) and HSL refined the study design and prepared action plans and communications for potential results.
- Study participants were recruited from three allotment sites with raised soil lead. Participating gardeners recruited a non-allotment gardening friend or neighbour of same gender and similar age to be their control.
- To account for confounders, participants provided tap water samples, home dust samples, atmospheric deposition samples and completed a questionnaire on potential exposure factors including demographics, lifestyle, occupations and hobbies, home characteristics and gardening habits.
- On their allotment sampling day the participants brought their home samples, provided blood and saliva samples and helped the team collect soil, vegetable and fruit samples from their plots.
- Lead in bloods, tap waters and soils have been analysed first, along with questionnaire data.

Total lead in allotment topsoils



Home sample packs



Sampling crew

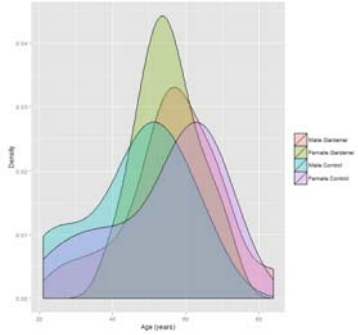
In the field

Initial findings

Sampling took place in September and October 2015. 44 allotment gardeners and 29 controls took part in the study. Participants' ages ranged from 21 to 84 years. The distribution of ages between gardeners, controls and sexes is shown in Figure 2 and further cohort information is provided in Figures 3 & 4 and Table 2. More women (43) than men (30) took part. 19% of participants knew they still had lead water pipes at home, 71% of the controls and 36% of allotment gardeners didn't know. Only four participants were current smokers. Three male gardeners and one control had a current occupation that might sometimes expose them to lead (construction and renovation). Years of allotment gardening ranged from 1 to 25 yrs with a median of 8 for females and 4 for males. Many participants also worked other gardens (70% of gardeners, 55% controls). Average time per week spent on the allotment in the growing season ranged from 0.5 to 36 hours. 31% usually washed their hands before eating on site, 31% always and 5% never.

Next steps….. Lots more sample analysis, informing participants of blood and tap water results, analysis of dose response relationships and developing a more appropriate guidance value for lead in allotment soils.

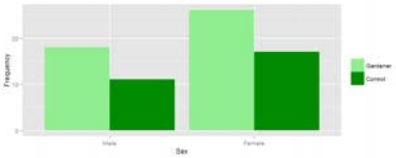
Participant age distribution



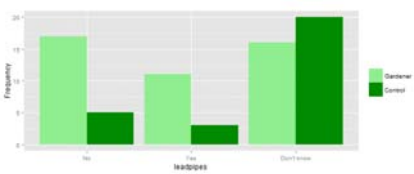
Cohort characteristics

		Female		Male	
		Allotment	Control	Allotment	Control
	number	26	17	18	11
age (yrs)	min	39	24	26	21
	median	55	61	57	48
	max	72	73	84	67
smokers (participant numbers)	never	15	11	9	4
	ex	10	6	7	6
	current	1	0	2	1
hand to mouth behaviour	yes	6	2	3	5
alcohol (units per week)	min	0	0	0.5	0
	median	6	12	10	8
	max	30	35	40	25
lead domsestic water pipes	no	9	2	8	3
	yes	4	3	7	0
	don't know	13	12	3	8
activities with lead exposure	previous hobby	3	1	2	2
	previous occupation	1	1	0	0
	current hobby	2	0	0	2
	current occupation	0	0	3	1
year working allotments	min	1	-	2	-
	median	8	-	4	-
	max	25	-	18	-
garden elsewhere	yes	21	11	8	5
	profesionally	1	-	1	-
handwashing at allotment	always	7	-	7	-
	usually	10	-	4	-
	sometimes	8	-	5	-
	never	1	-	1	-
hours per week on allotment	min-max	0.5-24	-	0.13-36	-
	median	5	-	5	-

Participant gender distribution



Home lead pipes distribution



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2.DEFRA, Category 4 Screening Levels for Assessment of Land Affected by Contamination, 2014

Newcastle Allotments Lead Biomonitoring Study: an investigation into the relationship between allotment soil lead concentrations and the blood lead concentration of gardeners.

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Abstract

In the UK, the current soil screening level for a 'low level toxicological concern' for lead in allotments is 80 mg/kg (DEFRA, 2014). This soil screening level is 10 times lower than that observed on many allotments across Newcastle, a city with a long industrial heritage in NE England. Detailed quantitative risk assessments have been previously carried out on Newcastle's allotment gardens and Newcastle City Council concluded that, on balance, gardening activities and consumption of vegetables from these sites is a greater benefit than risk to health, however, there is considerable uncertainty in the exposure modelling, with the association between concentrations of lead in soil and blood remaining uncharacterised.

The aim of this study was to determine the relationship between concentrations of lead in garden soils and the blood lead concentration of gardeners to give confidence to regulators who must decide the suitability of a site. Study participants were recruited from three Newcastle allotment sites (BR, TS and MS). Pseudo-total soil lead (aqua-regia extraction) ranged from 62 – 840 mg/kg at BR (mean= 403 mg/kg; n=86), 92 – 810 at TS (mean= 360 mg/kg; n=96) and 58 – 1300 at MS (mean= 312 mg/kg; n=102). Gardeners (n=44) recruited non-allotment gardening neighbours as controls (n = 29). Participants provided blood and saliva samples and helped the team collect soil, vegetable and fruit samples from their plots. To account for confounders, participants provided tap water samples, home dust samples, atmospheric deposition samples and completed a questionnaire on potential exposure factors.

This paper presents the results of the blood Pb survey in conjunction with the questionnaire data to show that urban agriculture on sites containing lead from common urban sources, even at concentrations up to 10 times over the current soil screening value does not result in significantly raised blood lead.

*Speaker

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Keywords: Blood lead, soil, urban gardens

Newcastle Allotments Lead Biomonitoring Study (NABS)

Lindsay Bramwell[ab], J. Entwistle[c] , J. Morton[d], T. Pless-Mulloli[b], J. Dean[c] , P. Amaibi[c] , M. Deary[c] , M. Cave[e] , J. Wragg[e]
[a]Newcastle City Council, [b]Newcastle University, [c]Northumbria University, [d]Health & Safety Laboratory, [e]British Geological Survey

1. Introduction

Allotment gardens are so much more than a source of fresh fruit and vegetables; they provide integration for communities, connection with nature, skills sharing, spirituality and therapy.

Newcastle's (NE England) residential gardens and allotments frequently contain raised Pb concentrations resulting from years of coal fire ash used as a soil improver (local coal contains elevated Pb) and ash from bonfires containing old window frames coated with Pb paint.

Recent UK government recommendations for safe Pb levels in allotment soil[1] are 10 times lower than those in Newcastle and many other urban areas in the UK and beyond. The aim of this study was to gather evidence on the relationship between concentrations of Pb in garden soils and bloods.

Fig.1: Field Sampling

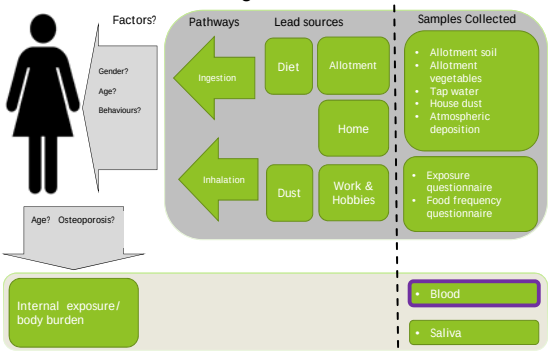

Fig.2: Study Design - Conceptual Exposure Model

2. Methods

- Study participants were recruited from three allotment sites and participating gardeners recruited a non-allotment gardening neighbour of same sex and similar age to be their control. 44 allotment gardeners and 29 controls took part in the study.
- Soil and produce samples were collected in triplicate from 3 locations on each sampled allotment (Fig 1). Total Pb was determined by ED-XRF and aqua-regia (n = 284 samples), with bioaccessibility (UBM protocol) determined on a sub-set of samples (n = 7) at each site.
- To account for confounders, participants provided tap water, home dust, and atmospheric deposition samples and completed a questionnaire on potential exposure factors including demographics, lifestyle, occupations and hobbies, home characteristics and gardening habits.

µg/dL Pb	Min	Median	P95	Max
Control	0.7	1.3	2.9	2.9
Gardener	0.6	1.55	3.7	11.4
All	0.6	1.5	3.1	11.4

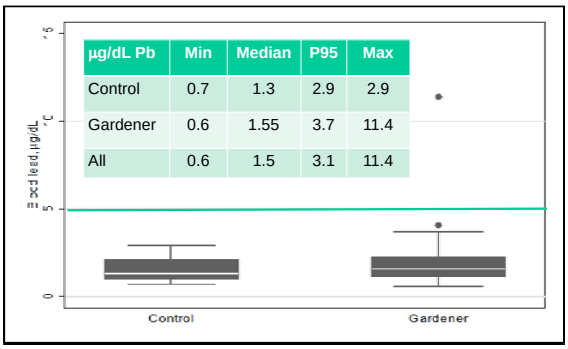

Fig.3: Blood Pb concentrations (µg/dL)

3. Initial findings & CLEA[1] model comparisons

Lead in bloods (Fig 3), tap waters and soils (Fig 4) have been analysed to date, along with the questionnaire data. Participants' ages ranged from 21 to 84 years, 4 were current smokers and 4 had a current occupation that might sometimes expose them to Pb (construction & renovation).

- ✓ **Blood Lead Levels (BLL):** When taking in account the additional factors covered in our questionnaire the gardeners did have higher BLLs than the controls (p=0.000), soil lead concentration (p=0.036) and years of allotment gardening became significant (p=0.012) as well as fraction of home-grown green veg (p= 0.06), herbaceous fruit (p=0.058) and root vegetables (p=0.012) consumed.
- ✓ **Diet:** Produce type consumption rate and the consumption fraction of homegrown produce (HF) is a key exposure pathway and an uncertainty identified in the sensitivity analyses of the CLEA model. Although gardeners tended to consume more fruit/vegetables than controls (Table 1), statistically there was no evidence of any difference in consumption rates. One of the modifications proposed in the CLEA update[1] is the use of central tendency values for fruit & vegetable consumption rates rather than 90th percentile values; with the exception of the 'top two' whereby 90th percentile consumption rates are used for the two homegrown produce groups expected to give the highest exposure for that contaminant, which for Pb are green vegetables and tubers. NABS data suggests a return to using at least the 90th percentile values for all fruit & vegetable, not just the 'top two (Table 1), whilst the 50th percentile NABS data (for gardeners) agrees well with the high end % HF used in the CLEA allotments model, except for herbacecous fruit & shrubs (Table 2).

Table 1: Consumption rate for fruit and vegetable categories

		Vegetable (g fw kg^{-1} bw day^{-1})			Fruit (g fw kg^{-1} bw day^{-1})		
NABS P90	Source	Green	Root	Tuber	Herb.	Shrub	Tree
Gardener	NABS	2.46	2.17	2.44	2.48	0.71	2.29
Control	NABS	1.95	1.63	1.69	1.96	0.33	2.21
	CLEA	**2.36 (90th)**	**0.6 (50th)** 1.12 (90th)	**2.35 (90th)**	**0.69 (50th)** 1.29 (90th)	**0.09 (50th)** 0.18 (90th)	**1.27 (50th)** 2.38 (90th)

- ✓ **Allotment holders behaviour:** Average time per week spent on the allotment in the growing season ranged from 0.5 to 36 hours, and modal duration of visit was 2-4 hours. The NABS data accords well with assumptions made in CLEA.
- ✓ **Soils:** Bioaccessible concentrations (median % bioaccessibilities), ranged from 58 – 608 mg/kg at BR (63%), 227 – 705 mg/kg at TS (55%) and 162 – 497 mg/kg at MS (65%) (Fig 4). Relative Bioaccessibility of 0.6 in CLEA model equates well with our determined bioaccessibilities.

Table 2: % Homegrown Fraction (%HF)

		% of homegrown/free produce consumed			
		CLEA data		NABS (gardeners) data	
		UK pop^{n} (P50)	High end	P50	P95
Vegetables	green	5	33	35	71
	root	6	40	35	61
	tuber	2	13	8	95
Fruit	herbaceous	6	4	21	79
	shrub	9	6	58	100
	tree	4	27	0	54

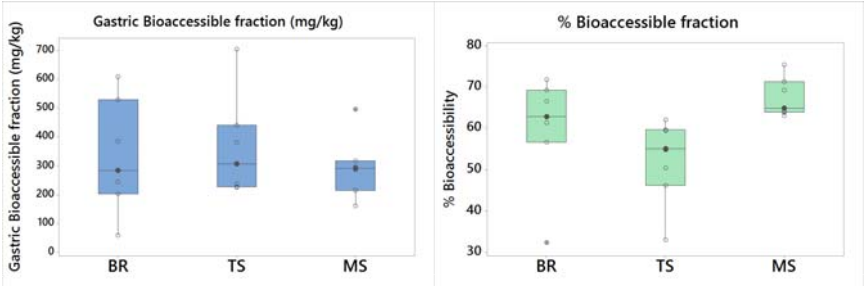

Fig. 4: Bioaccessibility

4. Next steps……..

- ✓ Analyse the fruit and vegetable samples to investigate soil to plant concentration factors and dietary lead intake rates.
- ✓ Data interrogation to determine the most important predictors of blood lead levels.
- ✓ Undertake sensitivity analysis using the Carlisle and Wade Model as the preferred model for modelling the relationship between intake and blood lead for adults[2] .
- ✓ Soil sequential fractionation in progress.
- ✓ Soil mineralogy in progress.

Acknowledgments & References

Field and Lab support provided by NU UG students Lauren Holden, Nicole Houghton & Joshua Hui. Water analysis by Northumbrian Water.

1. DEFRA, Category 4 Screening Levels for Assessment of Land Affected by Contamination, 2014.
2. EFSA, European Food Safety Authority, Scientific Opinion on Lead in Food (2010).

Appendix E

Supplementary Information:

Associations between human exposure to polybrominated diphenyl ether flame retardants via diet and indoor dust, and internal dose: A systematic review

Associations between human external and internal exposure to polybrominated diphenyl ether) flame retardants: A systematic review

Supplementary information

1) Search Strategy and Terms

The study will be conducted according to the PRISMA statement.

Data sources: Four electronic databases (Pubmed, EMBASE, Web of Science, Scopus) searched with the assistance of I.H.S. Information Specialist.

PBDE=polybrominated diphenyl ethers

Search terms:

EMBASE 1974 to 2015 week 4
PBDE exposure in humans, full text, English language:

1.($bde OR pbde OR pbdes OR (polybrominated and ('diphenyl' de OR diphenyl) and ('ethers' de OR ethers))) AND
2.(serum$ OR plasma$ OR blood$ or milk$ OR internal OR 'body burden'$ OR exposure$) AND
3. (diet$ OR food$ OR dust$ OR air$ OR indoor$ OR environment$ OR exposure$ OR factor$ OR lifestyle$ OR source$ OR behav$) AND
4. (match$ OR pair$ OR relation$ OR association$ OR evidence$ OR predict$) AND

($bde OR pbde OR pbdes OR (polybrominated and ('diphenyl' de OR diphenyl) and ('ethers' de OR ethers))) AND (serum$ OR plasma$ OR blood$ or milk$ OR internal OR body burden$ OR exposure$) AND (diet$ OR food$ OR dust$ OR air$ OR indoor$ OR environment$ OR exposure$ OR factor$ OR lifestyle$ OR source$ OR behav$) AND (match$ OR pair$ OR relation$ OR association$ OR evidence$ OR predict$).ti,ab

Searched for in titles, keywords and abstracts

Additional searching:

Reference list review
Any article deemed suitable by reviewers is included for closer examination.

Inclusion/exclusion criteria

Inclusion criteria:

Studies were included if they were published in a peer-reviewed journal, written in English and reported investigation of correlation between paired human internal (blood and milk only) and external (dust and diet only) PBDE concentrations.
Papers were excluded in internal and external measurements were not paired, or if the external measurement investigated was purely occupational, from a hobby or a specific type of food.

2) PRISMA Checklist of items for inclusion when reporting a systematic review or meta-analysis

Section/topic	*#*	*Checklist item*	*Reported on page #*
TITLE			
Title	1	Identify the report as a systematic review, meta-analysis, or both.	1
ABSTRACT			
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	3
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	4
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number.	n/a
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.	4
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	4
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	SI1
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	4

Section/topic	*#*	*Checklist item*	*Reported on page #*
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	4-5
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	Tables 1 & 2
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	n/a
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means).	n/a
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis.	n/a
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	n/a
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	n/a
RESULTS			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	Figure 1
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	Tables 1 & 2
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome-level assessment (see Item 12).	n/a
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group and (b) effect estimates and confidence intervals, ideally with a forest plot.	n/a
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	n/a

Section/topic	*#*	*Checklist item*	*Reported on page #*
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15).	n/a
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	n/a
DISCUSSION			
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., health care providers, users, and policy makers).	12
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review level (e.g., incomplete retrieval of identified research, reporting bias).	17 & 21
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	21
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	22

Appendix F

Supplementary Information:

PBDEs and PBBs in human serum and breast milk from cohabiting UK couples

Supplementary Data Table S1a: UK individuals PBDE and PBB serum concentrations (ng/g lipid weight)

Couple	Sex	Week	Lipid %	BDE-17	BDE-28	BDE-47	BDE-49	BDE-66	BDE-71	BDE-77	BDE-85	BDE-99	BDE-100
1(i)	F	b	0.631	<0.033	0.075	1.259	0.058	0.067	<0.001	<0.017	<0.029	0.534	0.183
1(ii)	F	a	0.33	<0.036	0.127	1.548	<0.121	<0.415	<0.036	<0.036	<0.055	<0.738	0.2
1(i)	M	b	0.459	<0.097	<0.37	<3.313	0.406	<0.37	<0.032	<0.032	<0.081	1.982	0.244
1(ii)	M	a	0.57	<0.023	0.102	1.219	0.09	<0.257	<0.023	<0.023	0.034	0.519	0.147
2(i)	F	b	0.797	<0.023	0.041	0.438	0.029	0.041	<0.001	<0.012	<0.02	0.245	0.064
2(ii)	F	a	0.37	<0.031	0.094	1.053	0.11	<0.358	<0.031	<0.031	0.047	<0.636	<0.063
2(i)	M	b	0.737	<0.029	0.065	1.036	0.043	0.058	<0.001	<0.014	0.036	0.913	0.355
2(ii)	M	a	0.55	<0.019	0.102	1.649	0.093	<0.211	<0.019	<0.019	0.056	1.26	0.519
3	F	a	0.49	<0.043	0.064	0.639	0.053	0.064	<0.001	<0.021	<0.037	<0.426	0.053
3	M	a	0.775	<0.06	<0.226	<2.023	<0.217	<0.226	<0.02	<0.02	0.04	0.784	0.109
4	F	a	0.34	<0.077	<0.293	<2.624	<0.282	<0.293	<0.026	<0.026	<0.045	0.991	0.116
4	M	a	0.312	<0.143	<0.545	<4.87	0.645	0.788	<0.048	<0.048	0.263	5.612	0.573
5	F	a	0.354	<0.084	<0.32	<2.861	<0.307	<0.32	<0.028	<0.028	0.126	1.669	0.224
5	M	a	0.934	<0.048	<0.181	<1.616	0.214	0.269	<0.016	<0.016	0.087	1.379	0.174
6	F	a	0.251	<0.079	0.099	1.269	0.099	0.119	<0.001	<0.04	<0.069	0.793	<0.079
6	M	a	0.481	<0.044	0.076	1.013	0.076	0.065	<0.001	<0.022	<0.038	0.512	0.196
7	F	a	0.734	<0.026	0.032	0.363	<0.029	0.032	<0.001	<0.013	<0.022	<0.255	<0.026
7	M	a	0.543	<0.048	0.06	0.741	0.06	0.06	<0.001	<0.024	<0.041	<0.478	<0.06
8	F	a	0.348	<0.056	0.07	0.797	<0.063	0.084	<0.001	<0.028	<0.048	<0.559	0.07
8	M	a	0.588	<0.034	0.051	0.615	0.051	0.06	<0.001	<0.017	<0.03	0.35	0.051
9	F	a	0.359	<0.087	<0.332	3.346	0.495	0.553	0.029	<0.029	0.189	3.812	0.436
9	M	a	0.505	<0.07	<0.267	<2.386	<0.256	<0.267	<0.023	<0.023	<0.082	1.509	0.152
10	F	a	0.329	<0.095	<0.36	<3.217	0.394	<0.36	<0.032	<0.032	0.126	2.177	0.268
10	M	a	0.269	<0.137	<0.52	<4.652	<0.5	0.547	<0.046	<0.046	0.182	2.692	0.297

Notes: (i) 1st sample week, (ii) 2nd sample week, i= Indicative value

Supplementary Data Table S1b: UK individuals PBDE and PBB serum concentrations (ng/g lipid weight)

Couple	Sex	Week	Lipid %	BDE-119	BDE-126	BDE153	BDE138	BDE 154	BDE-183	BDE-209	BB-15	BB-49	BB-52
1(i)	F	b	0.631	<0.017	<0.017	0.183	<0.033	0.033	0.033	2.56	<0.017	<0.001	<0.001
1(ii)	F	a	0.33	<0.001	<0.018	0.255	<0.073	<0.063	0.073	<7.89	<0.036	<0.001	<0.001
1(i)	M	b	0.459	<0.032	<0.016	0.666	<0.13	0.097	0.114	<3.95	<0.975	<0.001	<0.032
1(ii)	M	a	0.57	<0.011	<0.001	0.722	<0.045	<0.039	0.034	<4.89	<0.023	<0.001	<0.001
2(i)	F	b	0.797	<0.012	<0.012	0.257	<0.023	<0.023	0.023	<1.13i	<0.012	<0.001	<0.001
2(ii)	F	a	0.37	<0.001	<0.016	0.173	<0.063	<0.054	<0.044	<6.81	<0.031	<0.001	<0.001
2(i)	M	b	0.737	<0.014	<0.014	2.594	<0.043	0.072	0.159	2.82i	<0.014	<0.001	<0.001
2(ii)	M	a	0.55	<0.028	<0.001	4.047	<0.037	0.148	0.194	4.91	<0.019	<0.001	<0.001
3	F	a	0.49	<0.021	<0.021	0.181	<0.043	<0.032	<0.043	<2.07i	<0.021	<0.001	<0.001
3	M	a	0.775	<0.02	<0.001	0.347	<0.079	<0.04	0.05	<2.41	<0.595	<0.001	<0.02
4	F	a	0.34	<0.026	<0.001	0.27	<0.103	0.09	<0.063	<3.13	<0.772	<0.001	<0.026
4	M	a	0.312	<0.048	<0.072	1.051	<0.191	0.382	0.334	19.8	<1.433	<0.001	<0.048
5	F	a	0.354	<0.028	<0.014	0.491	0.112	<0.098	<0.069	<3.41	<0.841	<0.001	<0.028
5	M	a	0.934	<0.016	<0.016	0.586	<0.063	0.063	0.103	<1.93	<0.475	<0.008	<0.016
6	F	a	0.251	<0.04	<0.04	0.337	<0.079	<0.056	0.099	<3.85	<0.04	<0.001	<0.001
6	M	a	0.481	<0.022	<0.022	0.479	<0.044	0.054	0.142	<2.11	<0.022	<0.001	<0.001
7	F	a	0.734	<0.013	<0.013	0.115	<0.026	<0.018	<0.026	<1.24	<0.013	<0.001	<0.001
7	M	a	0.543	<0.024	<0.024	0.227	<0.048	<0.036	<0.048	<2.32	<0.024	<0.001	<0.001
8	F	a	0.348	<0.028	<0.028	0.252	<0.056	<0.04	<0.056	<2.71i	<0.042	<0.001	<0.001
8	M	a	0.588	<0.017	<0.017	0.282	<0.034	<0.024	0.043	<1.66i	<0.017	<0.001	<0.001
9	F	a	0.359	<0.044	<0.044	0.975	<0.116	0.218	0.204	<3.54	<0.873	<0.001	<0.029
9	M	a	0.505	<0.023	<0.023	0.491	<0.094	<0.058	<0.057	<2.85	<0.702	<0.001	<0.023
10	F	a	0.329	<0.032	<0.047	0.394	<0.126	0.079	0.095	<3.84	<0.946	<0.001	<0.032
10	M	a	0.269	<0.068	<0.068	0.661	<0.182	<0.091	0.137	6.09	<1.369	<0.001	<0.046

Notes: (i) 1st sample week, (ii) 2nd sample week, i= Indicative value

Supplementary Data Table S1c: UK individuals PBDE and PBB serum concentrations (ng/g lipid weight)

Couple	Sex	Week	Lipid %	BB-80	BB-101	BB-153	BB-209
1(i)	F	b	0.631	<0.001	<0.017	0.083	<0.23
1(ii)	F	a	0.33	<0.001	<0.036	0.073	<0.18
1(i)	M	b	0.459	<0.001	<0.049	<0.032	<0.45
1(ii)	M	a	0.57	<0.001	<0.023	0.034	<0.11
2(i)	F	b	0.797	<0.001	<0.012	0.018	<0.16
2(ii)	F	a	0.37	<0.001	<0.031	<0.016	<0.16
2(i)	M	b	0.737	<0.001	<0.014	0.63	<0.2
2(ii)	M	a	0.55	<0.001	<0.019	0.908	<0.09
3	F	a	0.49	<0.001	<0.043	<0.032	<0.29
3	M	a	0.775	<0.001	<0.02	<0.04	<0.28
4	F	a	0.34	<0.001	<0.026	<0.026	<0.36
4	M	a	0.312	<0.001	<0.048	<0.072	<0.67
5	F	a	0.354	<0.001	<0.07	<0.028	<0.39
5	M	a	0.934	<0.001	<0.04	0.055	<0.22
6	F	a	0.251	<0.001	<0.04	<0.04	<0.55
6	M	a	0.481	<0.001	<0.044	<0.022	<0.3
7	F	a	0.734	<0.001	<0.013	<0.013	<0.18
7	M	a	0.543	<0.001	<0.024	0.036	<0.33
8	F	a	0.348	<0.001	<0.028	<0.042	<0.39
8	M	a	0.588	<0.001	<0.017	0.051	<0.24
9	F	a	0.359	<0.015	<0.044	0.073	<0.41
9	M	a	0.505	<0.001	<0.058	0.058	<0.33
10	F	a	0.329	<0.001	<0.032	<0.032	<0.44
10	M	a	0.269	<0.001	<0.091	<0.046	<0.64

Supplementary Data Table S2. UK individuals PBDE and PBB breastmilk concentrations (ng/g lipid weight)

Participant Reference	Week	Fat %	BDE-17	BDE-28	BDE-47	BDE-49	BDE-66	BDE-71	BDE-77	BDE-85	BDE-99	BDE-100	BDE-119	BDE-126
1F(ii)	a	2.7	0.014	0.313	13.09	0.105	0.129	<0.001	0.002	0.326i	3.741	2.193	0.005	<0.002
2F(ii)	a	2.68	0.005	0.094	2.045	0.024	0.028	<0.001	<0.001	0.048	0.787	0.427	0.003	<0.001
4F	a	1.02	<0.005	0.022	0.323	<0.027	<0.032	<0.003	<0.003	<0.013	0.115	0.072	0.007	<0.003
5F	a	0.97	<0.01	0.073	1.705	<0.054	<0.064	<0.005	<0.005	0.039	0.452	0.833	0.008	<0.005
9F	a	4.56	<0.004	0.087	1.798	0.035	0.035	<0.002	<0.002	0.041	1.038	0.445	0.007	<0.002
9F x	a	4.99	0.008	0.104	2.51	0.052	0.045	<0.002	<0.002	0.059	1.541	0.552	0.007	<0.002
10F	a	2.54	<0.002	0.138	3.532	0.027	0.03	<0.002	0.002	0.064i	0.966	1.239	0.009	<0.002

Participant Reference	Week	Fat %	BDE153	BDE138	BDE 154	BDE-183	BDE-209	BB-15	BB-49	BB-52	BB-80	BB-101	BB-153	BB-209
1F(ii)	a	2.7	0.819	0.044	0.188	0.056	0.99	<0.011	<0.001	<0.001	<0.001	0.007	0.786	<0.05
2F(ii)	a	2.68	1.104	0.015	0.035	0.021	0.34	<0.007	<0.001	<0.001	<0.001	<0.002	0.079	<0.05
4F	a	1.02	0.704	<0.008	0.013	0.022	<0.37	<0.058	<0.002	<0.002	<0.002	<0.008	0.059	<0.05
5F	a	0.97	1.676	<0.016	0.054	0.044	1.04	<0.114	<0.002	<0.002	<0.002	<0.01	0.078	<0.05
9F	a	4.56	0.908	0.015	0.077	0.067	0.7	<0.044	<0.002	<0.002	<0.002	<0.008	0.279	<0.05
9F x	a	4.99	0.933	0.013	0.113	0.084	1.17	<0.04	<0.002	<0.002	<0.002	<0.005	0.283	<0.05
10F	a	2.54	1.387	0.017	0.113	0.226	0.2	<0.019	<0.002	<0.002	<0.002	<0.004	0.062	<0.05

Notes: (i) 1st sample week, (ii) 2nd sample week, i= Indicative value, x - additional sample collected 24 hours after sample 9F

Appendix G

Supplementary Information:

UK dietary exposure to PCDD/Fs, PCBs, PBDD/Fs, PBBs and PBDEs: comparison of results from 24-h duplicate diets and total diet studies

Supplementary Information Table A1a. 24 Hour duplicate diet sample PBDE, PBB and PBDD/F concentrations (ug/kg lw)

				PBDEs										
participant reference	participant weight (kg)	DD Lipid %	DD mass (g)	BDE-17	BDE-28	BDE-47	BDE-49	BDE-66	BDE-71	BDE-77	BDE-85	BDE-99	BDE-100	BDE-119
1 (i) F	80.3	2.16*	2360	0.003	0.012	0.320	0.013	0.010	<0.002	<0.002	0.013	0.403	0.078	<0.002
1 (ii) F	81.8	6.33	1186	0.003	0.020	0.856	0.095	0.018	<0.001	<0.001	0.003	0.109	0.205	0.005i
1 (i) M	71.3	2.26*	1876	<0.002	0.009	0.274	0.009	0.008	<0.002	<0.002	0.010	0.335	0.069	<0.002
1 (ii) M	71.9	3.95	1018	0.003	0.021	0.793	0.097	0.019	<0.001	<0.001	<0.005	0.126	0.234	0.005
2 (i) F	89.4	6.34	1245	<0.002	0.003	0.098	<0.005	0.006	<0.002	<0.002	<0.002	0.113	0.022	<0.002
2 (ii) F	84.5	6.48	746	0.002	0.007	0.214	0.009	0.010	<0.001	<0.001	0.007	0.210	0.025	<0.001
2 (i) M	77.4	3.98	1236	<0.002	0.003	0.091	<0.007	<0.006	<0.002	<0.002	<0.002	0.102	0.015	<0.002
2 (ii) M	76.7	5.93	987	0.001	0.006	0.126	0.007	0.006	<0.001	<0.001	<0.003	0.140	0.017	<0.001
3 F	62.4	6.7	573	<0.002	0.003	0.047	0.003	0.002	<0.002	<0.002	<0.002	0.050	0.008	<0.002
3 M	78.7	3.9	720	<0.002	0.006	0.080	0.007	0.008	<0.002	<0.002	<0.002	0.088	0.014	<0.002
4 F	75.7	6.32	1249	<0.002	<0.005	0.081	0.007	0.006	<0.002	<0.002	0.003	0.096	0.015	<0.002
4 M	81.9	7.08	1293	0.002	0.019	0.163	0.048	0.019	<0.002	<0.002	<0.002	0.059	0.039	<0.002
5 F	78.9	5.6	1022	0.004	0.017	0.128	0.023	0.023	<0.002	<0.002	0.003	0.166	0.025	<0.002
5 M	100.8	4.58	1360	0.003	0.020	0.295	0.050	0.063	<0.002	0.004	<0.002	0.443	0.060	<0.002
6 F	83.6	4.57	720	<0.002	<0.007	0.120	<0.009	<0.009	<0.002	<0.002	<0.003	0.098	0.011	<0.002
6 M	82.2	4.15	992	<0.002	<0.009	0.086	0.006	0.006	<0.002	<0.002	<0.002	0.095	0.014	<0.002
7 F	80.8	4.48	1175	<0.002	<0.007	0.079	0.006	0.006	<0.002	<0.002	<0.002	0.092	0.013	<0.002
7 M	79.5	6.89	946	<0.002	0.003	0.076	0.006	0.007	<0.002	<0.002	<0.002	0.098	0.014	<0.002
8 F	62.6	10.38	795	<0.002	0.007	0.090	0.006	0.005	<0.002	<0.002	<0.002	0.089	0.023	<0.002
8 M	67.4	8.06	1412	<0.002	0.005	0.123	<0.004	0.005	<0.002	<0.002	<0.002	0.125	0.025	<0.002
9 F	73.3	8.74	1120	<0.002	0.003	0.070	<0.004	<0.005	<0.002	<0.002	<0.002	0.068	0.012	<0.002
9 M	78.2	12.92	430	<0.002	<0.002	0.035	<0.003	<0.003	<0.002	<0.002	<0.002	0.034	0.007	<0.002
10 F	67.6	4.74	1078	<0.002	0.005	0.073	<0.007	<0.008	<0.002	<0.002	<0.003	0.074	0.012	<0.002
10 M	91	4.6	700	<0.002	0.004	0.066	<0.006	<0.008	<0.002	<0.002	<0.003	0.069	0.015	<0.002

Notes: TEQ computed using PCDD/F 1998 TEFs, ND - not determined, i-indicative, *sample includes non-dairy liquids resulting in low solids content

Supplementary Information Table A1b. 24 Hour duplicate diet sample PBDE, PBB and PBDD/F concentrations (ug/kg lw)

									ortho PBBs					
participant reference	participant weight (kg)	DD Lipid %	DD mass (g)	BDE-126	BDE153	BDE138	BDE 154	BDE-183	BB-15	BB-49	BB-52	BB-80	BB-101	BB-153
1 (i) F	80.3	2.16*	2360	<0.002	0.036	0.007	0.032	0.016	<0.004	<0.002	<0.002	<0.002	<0.002	<0.002
1 (ii) F	81.8	6.33	1186	<0.001	0.048i	<0.003	0.058	0.010	1.266	nm	<0.001	<0.001	<0.001	<0.002
1 (i) M	71.3	2.26*	1876	<0.002	0.035	<0.002	0.027	0.014	<0.006	<0.002	<0.002	<0.002	<0.002	<0.002
1 (ii) M	71.9	3.95	1018	<0.001	0.015	<0.003	0.056	0.013	1.42	nm	0.00	<0.001	<0.001	<0.003
2 (i) F	89.4	6.34	1245	<0.002	0.033	<0.004	0.021i	<0.064	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
2 (ii) F	84.5	6.48	746	<0.001	0.055i	<0.003	0.021	0.010	<0.6173	nm	<0.001	<0.001	<0.001	<0.002
2 (i) M	77.4	3.98	1236	<0.002	0.013	<0.003	<0.005	0.003	<0.002	<0.002	<0.002	<0.002	<0.003	<0.002
2 (ii) M	76.7	5.93	987	<0.001	0.024i	<0.003	0.016	0.006	<0.6745	nm	<0.001	<0.001	<0.001	<0.001
3 F	62.4	6.7	573	<0.002	0.010	<0.002	0.003	0.006	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
3 M	78.7	3.9	720	<0.002	0.015	<0.002	0.005	0.008	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
4 F	75.7	6.32	1249	<0.002	0.027	0.005	0.008	0.012	<0.003	<0.002	<0.002	<0.002	<0.002	<0.002
4 M	81.9	7.08	1293	<0.002	0.012	<0.002	0.033	0.008	<0.004	<0.002	<0.002	<0.002	<0.002	<0.002
5 F	78.9	5.6	1022	<0.002	0.047	<0.002	0.017	0.027	<0.004	<0.002	<0.002	<0.002	<0.002	<0.002
5 M	100.8	4.58	1360	<0.002	0.093	<0.005	0.033i	0.031	<0.002	<0.002	<0.002	<0.002	<0.003	<0.002
6 F	83.6	4.57	720	<0.002	0.022	<0.002	0.033i	0.012	<0.005	<0.002	<0.002	<0.002	<0.002	<0.002
6 M	82.2	4.15	992	<0.002	0.014	<0.002	0.012i	0.006	<0.006	<0.002	<0.002	<0.002	<0.002	<0.002
7 F	80.8	4.48	1175	<0.002	0.016	<0.002	0.006	0.018	<0.009	<0.002	<0.002	<0.002	<0.002	<0.002
7 M	79.5	6.89	946	<0.002	0.027	<0.002	0.011	0.015	<0.01	<0.002	<0.002	<0.002	<0.002	<0.002
8 F	62.6	10.38	795	<0.002	0.026	<0.002	0.009	0.016	<0.01	<0.002	<0.002	<0.002	<0.002	<0.002
8 M	67.4	8.06	1412	<0.002	0.029	<0.002	0.016i	0.011	<0.008	<0.002	<0.002	<0.002	<0.002	<0.002
9 F	73.3	8.74	1120	<0.002	0.011	<0.002	0.007	0.010	<0.008	<0.002	<0.002	<0.002	<0.002	<0.002
9 M	78.2	12.92	430	<0.002	0.008	<0.002	<0.005	0.005	<0.008	<0.002	<0.002	<0.002	<0.002	<0.002
10 F	67.6	4.74	1078	<0.002	0.017	<0.002	0.005	0.032	<0.014	<0.002	<0.002	<0.002	<0.002	<0.002
10 M	91	4.6	700	<0.002	0.019	<0.002	0.005	0.076	<0.014	<0.002	<0.002	<0.002	<0.002	<0.002

Notes: TEQ computed using PCDD/F 1998 TEFs, ND - not determined, i-indicative, *sample includes non-dairy liquids resulting in low solids content

Supplementary Information Table A1c. 24 Hour duplicate diet sample PBDE, PBB and PBDD/F concentrations (ug/kg lw)

				Decas		Non-Ortho PBBs							
participant reference	participant weight (kg)	DD Lipid %	DD mass (g)	BDE-209	BB-209	PBB77	PBB126	PBB169	237-TriBDD	2378-TetraBDD	12378-PentaBDD	123478/123678-HexaBDD	123789-HexaBDD
1 (i) F	80.3	2.16*	2360	1.24	<0.05	<0.076	<0.009	<0.054	<0.018	<0.011	<0.054	<0.132	<0.104
1 (ii) F	81.8	6.33	1186	0.003i	<0.2532								
1 (i) M	71.3	2.26*	1876	3.13	<0.05	<0.064	<0.008	<0.046	<0.015	<0.017	<0.046	<0.111	<0.088
1 (ii) M	71.9	3.95	1018	<0.002	<0.1579								
2 (i) F	89.4	6.34	1245	0.68	<0.05	<0.064	<0.014	<0.019	<0.014	0.012	<0.043	<0.076	<0.055
2 (ii) F	84.5	6.48	746	<0.002	<0.1543								
2 (i) M	77.4	3.98	1236	0.46	<0.05	<0.083	<0.019	<0.025	<0.019	0.019	<0.056	<0.099	<0.05
2 (ii) M	76.7	5.93	987	<0.001	<0.1686								
3 F	62.4	6.7	573	0.82	0.30	<0.077	<0.03	<0.069	<0.015	<0.02	<0.04	<0.133	<0.109
3 M	78.7	3.9	720	1.56	0.12	<0.102	<0.039	<0.092	<0.02	<0.026	<0.052	<0.177	<0.144
4 F	75.7	6.32	1249	1.44	<0.05	0.067	<0.019	<0.033	<0.01	<0.005	<0.043	<0.143	<0.138
4 M	81.9	7.08	1293	<0.71	<0.05	0.055	<0.015	<0.026	0.017	0.011	<0.033	<0.111	<0.107
5 F	78.9	5.6	1022	1.28i	<0.05	0.048	<0.02	<0.035	<0.01	<0.008	<0.045	<0.151	<0.146
5 M	100.8	4.58	1360	1.44	<0.05	<0.076	<0.017	<0.023	0.028	<0.01	<0.051	<0.09	<0.039
6 F	83.6	4.57	720	2.68	<0.05	0.099	<0.029	<0.051	<0.015	<0.011	<0.066	<0.22	<0.213
6 M	82.2	4.15	992	0.79i	<0.05	<0.125	<0.015	<0.09	<0.03	<0.015	<0.09	<0.217	<0.172
7 F	80.8	4.48	1175	<0.09	<0.05	<0.096	<0.012	<0.069	<0.023	<0.014	<0.069	<0.167	<0.132
7 M	79.5	6.89	946	0.25	<0.05	<0.062	<0.013	<0.018	0.015	<0.022	<0.039	<0.079	<0.048
8 F	62.6	10.38	795	1.00	<0.05	<0.04	<0.008	<0.011	<0.005	<0.014	<0.025	<0.05	<0.031
8 M	67.4	8.06	1412	1.00	<0.05	<0.053	<0.011	<0.015	0.015	<0.019	<0.034	<0.068	<0.041
9 F	73.3	8.74	1120	0.50	0.08	<0.053	<0.011	<0.015	<0.005	<0.019	<0.034	<0.067	<0.041
9 M	78.2	12.92	430	0.31	<0.05	<0.021	<0.021	<0.042	<0.01	<0.013	<0.039	<0.052	<0.05
10 F	67.6	4.74	1078	0.54	<0.05	<0.092	<0.02	<0.026	0.029	<0.033	<0.059	<0.117	<0.072
10 M	91	4.6	700	0.78i	<0.05	<0.087	<0.018	<0.025	<0.009	<0.031	<0.055	<0.111	<0.068

Notes: TEQ computed using PCDD/F 1998 TEFs, ND - not determined, i-indicative, *sample includes non-dairy liquids resulting in low solids content

Supplementary Information Table A2a: 24 Hour duplicate diet sample PCDD/F and PCB concentrations (ug/kg lw)

			Ortho-PCB Results and Summary									
Participant ID	Participant body weight (kg)	DD lipid %	PCB18	PCB28	PCB31	PCB47	PCB49	PCB51	PCB52	PCB99	PCB101	PCB105
1 (i) F	80.3	2.16	0.06	0.08	0.09	0.11	0.06	0.02	0.22	0.19i	0.26	0.09
1 (i) M	71.3	2.26	0.06	0.10	0.09i	0.10	0.05	0.02	0.18	0.12	0.22	0.10
2 (i) F	89.4	6.34	0.04	0.04i	0.07	0.08	<0.03	0.01	0.03	<0.05	0.04	0.03
2 (i) M	77.4	3.98	0.06	0.07	0.08	0.14	<0.04	<0.03	0.06	<0.06	0.05	0.04
3 F	62.4	6.7	<0.01	0.13	0.08	0.07	<0.01	<0.01	<0.02	0.04	0.03	0.02
3 M	78.7	3.9	<0.01	0.09	<0.06	0.10	<0.02	<0.01	0.04	0.04i	0.04	0.02
4 F	75.7	6.32	0.03	0.03	<0.03	0.29	0.02	0.05	0.03	0.03	0.02	0.03
4 M	81.9	7.08	0.05i	0.09	0.10	0.08	0.09	<0.01	0.23	0.15	0.33	0.06
5 F	78.9	5.6	0.03	0.03i	<0.03	0.08	0.02	0.01	0.04	0.04	0.03	0.02
5 M	100.8	4.58	<0.03	0.05	<0.03	0.09	<0.03	<0.01	0.03	<0.06	<0.03	<0.02
6 F	83.6	4.57	0.07i	0.10i	0.11	0.17	0.03	0.03	0.05	0.07	0.04	0.04
6 M	82.2	4.15	0.06i	0.09	0.07	0.05	0.02	<0.01	0.04	0.06i	0.03	0.02
7 F	80.8	4.48	0.04	<0.03	0.09i	0.05	0.02	<0.01	0.04	0.06	0.03	0.03
7 M	79.5	6.89	0.04	0.05i	0.06	0.05	0.03	<0.01	0.04	0.08	0.03	0.03
8 F	62.6	10.38	0.07	0.09	<0.09	0.06	0.05	<0.01	0.13	0.07	0.09	0.03
8 M	67.4	8.06	0.04	0.08	0.10	0.09	0.04	0.01	0.09	0.13	0.07	0.06
9 F	73.3	8.74	0.04	0.06	0.05	0.04	0.02	<0.01	0.05	0.05	0.04	0.01
9 M	78.2	12.92	<0.02	<0.03	0.03i	0.06	0.01	0.02	0.03	0.03	0.02	0.01i
10 F	67.6	4.74	0.04	0.07i	<0.07	0.10	0.02	0.02	0.04	0.05	0.03	0.02
10 M	91	4.6	0.03	<0.07	<0.06	0.09	0.02	0.01	0.03	0.08	0.02	0.02

Notes: ND - not determined, i-indicative

Supplementary Information Table A2b: 24 Hour duplicate diet sample PCDD/F and PCB concentrations (ug/kg lw)

Participant ID	Participant body weight (kg)	DD lipid %	PCB114	PCB118	PCB123	PCB128	PCB138	PCB153	PCB156	PCB157	PCB167	PCB180
1 (i) F	80.3	2.16	<0.01	0.25	<0.01	0.06	0.33	0.32i	0.03	<0.01	0.01	0.07i
1 (i) M	71.3	2.26	<0.01	0.28	<0.01	0.05	0.34	0.32	0.04	<0.01	0.01	0.10
2 (i) F	89.4	6.34	<0.01	0.14	<0.01	0.04	0.23	0.29	0.02	<0.01	<0.01	0.14
2 (i) M	77.4	3.98	<0.02	0.11	<0.01	0.03	0.15	0.19	0.03	0.02	0.02	0.10
3 F	62.4	6.7	<0.01	0.09	<0.01	0.02	0.16	0.19	0.01	<0.01	<0.01	0.08
3 M	78.7	3.9	<0.01	0.08	<0.01	0.02	0.17	0.19	0.01	<0.01	<0.01	0.07
4 F	75.7	6.32	<0.01	0.08	<0.01	0.01	0.13	0.16	0.01	<0.01	<0.01	0.08
4 M	81.9	7.08	<0.01	0.20	<0.01	0.05	0.41	0.44	0.02	<0.01	0.02	0.08
5 F	78.9	5.6	<0.01	0.07	<0.01	0.01	0.10	0.11	0.01	<0.01	<0.01	0.05
5 M	100.8	4.58	<0.02	0.10	<0.01	0.03	0.16	0.17	0.03	0.01	<0.01	0.07i
6 F	83.6	4.57	<0.01	0.14	<0.01	0.03	0.18	0.20	0.01	<0.01	0.01	0.08
6 M	82.2	4.15	<0.01	0.09	<0.01	0.02	0.12	0.12	0.01	<0.01	<0.01	0.05i
7 F	80.8	4.48	<0.01	0.14	<0.01	0.02i	0.22	0.25	0.02	<0.01	0.01	0.10
7 M	79.5	6.89	<0.01	0.15	<0.01	0.03	0.21	0.25	0.02	0.01	0.02	0.12
8 F	62.6	10.38	<0.01	0.11	<0.01	0.02i	0.14	0.18	0.01	<0.01	<0.01	0.07
8 M	67.4	8.06	<0.01	0.22	<0.01	0.04	0.28	0.34	0.02	<0.01	0.01	0.12
9 F	73.3	8.74	<0.01	0.06	<0.01	0.02	0.15	0.18	<0.01	<0.01	<0.01	0.09
9 M	78.2	12.92	<0.01	0.04	<0.01	<0.01	0.06	0.06	<0.01	<0.01	<0.01	0.02
10 F	67.6	4.74	<0.01	0.07	<0.01	0.02	0.13	0.15	<0.01	<0.01	<0.01	0.07
10 M	91	4.6	0.01	0.14	<0.01	0.03	0.20	0.26	0.02	<0.01	<0.01	0.12

Notes: ND - not determined, i-indicative

Supplementary Information Table A2c: 24 Hour duplicate diet sample PCDD/F and PCB concentrations (ug/kg lw)

				Non-Ortho PCB				PCDD/F Results				
Participant ID	Participant body weight (kg)	DD lipid %	PCB189	PCB77	PCB81	PCB126	PCB169	2,3,7,8-TCDD	1,2,3,7,8-PeCDD	1,2,3,4,7,8-HxCDD	1,2,3,6,7,8-HxCDD	1,2,3,7,8,9-HxCDD
1 (i) F	80.3	2.16	<0.01	5.29	0.29	1.21	0.17	0.02	0.04	0.02i	0.07	0.03
1 (i) M	71.3	2.26	<0.01	3.92	0.34	1.83	0.26	0.02	0.06	0.02i	0.08	0.04
2 (i) F	89.4	6.34	<0.01	2.01	0.22	1.58	0.29	0.02	0.06	0.04	0.09	0.03
2 (i) M	77.4	3.98	<0.01	2.02	0.22	0.98	0.28	<0.01	0.04	<0.02	0.07	0.03i
3 F	62.4	6.7	<0.01	8.92	0.16	1.01	0.27	0.02	0.04i	<0.01	0.04	0.03
3 M	78.7	3.9	<0.01	5.28	0.17	0.92	0.23	<0.02	0.05	<0.02	0.05	<0.03
4 F	75.7	6.32	<0.01	2.81	0.24	0.98	0.17	0.02	0.04i	0.05	0.20	0.07
4 M	81.9	7.08	<0.01	9.18	0.62	1.69	0.26	<0.01	0.03	<0.01	0.06	<0.02
5 F	78.9	5.6	<0.01	2.22	0.22	0.75	0.18	0.03	0.08	0.03	0.07	0.03
5 M	100.8	4.58	<0.01	2.80	0.17	0.88	0.22	0.02	0.06i	0.04	0.11	0.06
6 F	83.6	4.57	<0.01	3.43	0.37	1.27	0.26	0.03	0.08	<0.02	0.06	0.04
6 M	82.2	4.15	<0.01	2.83	0.24	0.77	0.12	<0.01	0.04	<0.02	0.06	0.02
7 F	80.8	4.48	<0.01	3.11	0.24	1.55	0.41	0.02	0.08	0.03	0.11	0.04
7 M	79.5	6.89	<0.01	3.41	<0.44	1.34	0.48	0.05	0.11	<0.04	0.16	0.05
8 F	62.6	10.38	<0.01	6.04	0.54	1.23	0.36	0.02	0.05	0.05	0.09i	<0.02
8 M	67.4	8.06	<0.01	6.36	0.49	2.62	0.54	0.07i	0.16	0.05	0.16	0.08
9 F	73.3	8.74	<0.01	3.67	<0.38	0.55	0.14	0.03	<0.03	<0.02	0.07	0.03
9 M	78.2	12.92	<0.01	2.25	0.11	0.36	0.07i	0.01	<0.01	0.01	0.04	<0.01
10 F	67.6	4.74	<0.01	3.22	<0.66	0.65	0.19	0.03	0.06	0.03	0.10	0.04
10 M	91	4.6	<0.01	2.55	<0.62	1.21	0.41	0.03	0.06	0.07	0.14	0.03

Notes: ND - not determined, i-indicative

Supplementary Information Table A2d: 24 Hour duplicate diet sample PCDD/F and PCB concentrations (ug/kg lw)

Participant ID	Participant body weight (kg)	DD lipid %	1,2,3,4,6,7,8-HpCDD	OCDD	2,3,7,8-TCDF	1,2,3,7,8-PeCDF	2,3,4,7,8-PeCDF	1,2,3,4,7,8-HxCDF	1,2,3,6,7,8-HxCDF	1,2,3,7,8,9-HxCDF	2,3,4,6,7,8-HxCDF	1,2,3,4,6,7,8-HpCDF
1 (i) F	80.3	2.16	0.55	3.71	0.10	0.05	0.13	0.06	0.07	0.02	0.05	0.17
1 (i) M	71.3	2.26	0.57	3.48	0.07	0.03	0.16	0.08	0.06	<0.01	0.06	0.18
2 (i) F	89.4	6.34	0.34	1.62	<0.05	0.03	0.14	0.10	0.08	<0.01	0.07	0.15
2 (i) M	77.4	3.98	0.23	2.02	<0.06	<0.02	0.11	0.06	0.05	<0.02	0.05	0.09
3 F	62.4	6.7	0.24	1.82	0.04	0.02	0.08	0.09	0.06	<0.01	0.07	0.09
3 M	78.7	3.9	0.22	1.28	0.03	<0.03	0.13	0.08	0.07	<0.01	0.06	0.10
4 F	75.7	6.32	1.15	8.96	0.05	0.04	0.09	0.09	0.06	<0.01	0.05	0.16
4 M	81.9	7.08	0.16	0.95	0.25	0.05	0.07	0.06	0.04	<0.01	0.03	0.13
5 F	78.9	5.6	0.48	3.35	0.09i	0.08	0.17	0.11	0.10	<0.02	0.06	0.20
5 M	100.8	4.58	0.67	3.71	0.10	0.07	0.23	0.18	0.12	<0.01	0.11	0.30
6 F	83.6	4.57	0.17	1.09	0.04	<0.04	0.10	0.05	0.06	<0.01	0.04	0.06
6 M	82.2	4.15	0.19	1.08	<0.04	0.03	0.07	0.06	0.04i	<0.01	0.04	0.10
7 F	80.8	4.48	0.31	1.47	0.05	0.02	0.18	0.09	0.06	<0.01	0.06	0.14
7 M	79.5	6.89	0.35	0.91	0.05	<0.02	0.17	0.09	0.07i	<0.02	0.10	0.07
8 F	62.6	10.38	0.80	4.21	0.15	0.08	0.18	0.18	0.14	<0.01	0.18	0.22i
8 M	67.4	8.06	3.17	33.96	0.08	0.04	0.28	0.13	0.15	<0.01	0.12	0.93
9 F	73.3	8.74	0.18	1.31	<0.03	0.02	0.09	0.05	<0.03	<0.01	0.06	0.06
9 M	78.2	12.92	0.13	1.54	<0.03	0.02	0.03	0.02	0.02	<0.01	0.01	0.06
10 F	67.6	4.74	0.28	2.24	<0.05	<0.03	0.09	0.04	0.04	<0.01	0.07	0.09
10 M	91	4.6	0.27	2.52	<0.04	<0.03	0.17	0.05	0.07	<0.01	0.06	0.11

Notes: ND - not determined, i-indicative

Supplementary Information Table A2e: 24 Hour duplicate diet sample PCDD/F and PCB concentrations (ug/kg lw)

Participant ID	Participant body weight (kg)	DD lipid %	1,2,3,4,7,8, 9-HpCDF	OCDF
1 (i) F	80.3	2.16	0.02	0.24
1 (i) M	71.3	2.26	<0.02	0.24
2 (i) F	89.4	6.34	<0.02	0.06
2 (i) M	77.4	3.98	<0.02	0.06
3 F	62.4	6.7	<0.02	0.06
3 M	78.7	3.9	0.02	0.05
4 F	75.7	6.32	<0.02	0.05
4 M	81.9	7.08	<0.03	0.17
5 F	78.9	5.6	<0.02	0.12
5 M	100.8	4.58	0.04	0.16
6 F	83.6	4.57	<0.01	0.06
6 M	82.2	4.15	<0.02	0.09
7 F	80.8	4.48	<0.02	0.06
7 M	79.5	6.89	<0.02	0.07
8 F	62.6	10.38	0.06	0.35
8 M	67.4	8.06	0.06	1.03
9 F	73.3	8.74	<0.01	0.07
9 M	78.2	12.92	<0.01	0.04
10 F	67.6	4.74	<0.03	<0.08
10 M	91	4.6	0.02	0.26

Notes: ND - not determined, i-indicative

Supplementary Information Table A3: Contents of 24 hour duplicate diet samples

participant	**Notes on Duplicate Diet Sample Content**
1 (i) F	Porridge, full fat milk, biscuit, 2x choc ice, tomato and feta tart, tomato curry. Contains cups of tea
1 (i) M	Porridge, full fat milk, biscuit, 2x choc ice, tomato and feta tart, tomato curry. Contains cups of tea
2 (i) F	muesli + 1% fat milk, ham and cheese sandwiches, toast and butter, toast and peanut butter, pasta bake - beef mince and cheese sauce
2 (i) M	muesli and full fat milk, chicken wrap, large pasta bake, mince beef and cheese sauce
3 F	chocolate biscuit, 2 butter biscuits, crisps, 2 slices cheese, pork chop
3 M	2 slices beef, cereal bar, pork chop
4 F	granola oat milk, iced finger, crisps, goats butter, Brussels pate, hard and soft goats cheese, fried egg, beans and chips, rich tea biscuit, strawberry finger sweets
4 M	muesli, oat milk, oatcakes, mackerel and tomato, 2 eggs , beans and chips, 2 chunks chocolate
5 F	3 savoury muffins with cholesterol lowering margarine and peanut butter, meat substitute mince and mozzarella, 1 slice edam, coleslaw, beetroot salad, potato wedges, roasted peppers, meat substitute burger
5 M	cheese on toast, quiche, sausage, burger, chicken potato wedges, cheese
6 F	2 x cereal bars, Caesar dressing on salad, cheese, garlic flat bread, pasta with meat substitute mince, mini vanilla cupcake
6 M	coco pops + milk, pasta salad, pretzels, cereal bar, pasta meat substitute mince, garlic bread, mini cupcake
7 F	cornflakes + milk, beef burger, chips, noodle salad, pasta salad, green curry soup, 1/2 tin tuna, mayo, ice cream
7 M	2 beef burgers, 2 slices cheese, mayonnaise, chips, pasta salad with cheese, Thai veg soup, tuna toasty, cheese, toffee ice-cream, cheesecake
8 F	omelette, 1/2 jar mixed nuts, salad dressing, cottage cheese, sweets, 1 lamb sausage, 1 beef sausage, mayo,
8 M	muesli, nuts, milk, dates, 40g cheese, 10g butter, 2 x sausages
9 F	muesli, milk, crisps, ham and cheese sandwich, 1/2 pork pie, 1/2 chocolate bar, pasta pesto bacon,
9 M	1 slice Victoria sponge, 2 packs crisps, 3 slices bacon, 1 egg, mushrooms
10 F	Weetabix, rice milk, marshmallows, 2 handfuls peanuts, ham, olives, bread and oil, pasta with bacon and tomato sauce, 2 squares chocolate, burger,
10 M	toast butter and marmalade, boiled sweets, beef soup, beef burger, chocolate sweets

Appendix H

Supplementary Information:

Predictors of human PBDE body burdens for a UK cohort

SUPPLEMENTARY DATA

Predictors of human PBDE body burdens for a UK cohort

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19 pages, 13 tables, 2 figures

Cohort description

The twenty volunteers were aged between 26 and 43 years, with weight range 62-101 kg and BMI range 21-33, median and mean BMI both 26. The majority had office based indoor work environments, four worked outdoors. One participant worked in electronics retail, one repaired soft furnishings, another was an artist often working with fabrics. Six of the couples lived in urban environments and four had rural homes. One of the female participants was a vegetarian, one female had a strong lactose intolerance and therefore avoided dairy foods, another was nursing an infant with a dairy intolerance, two participants ate mainly organic food, and one participant did not eat beef. Parity among the women ranged from 0 to 3 children, and total amount of time spent breastfeeding over their whole life ranged from 0 to 60 months, with a median of 10 months and mean of 15 months. Seven of the women were on maternity leave at the time of the study. All participants described their health as either good, very good or excellent. Six participants were ex-smokers and two were current smokers. No participant had been present during a house fire but one had visited recent numerous fire scenes whilst previously employed with the emergency services. Five participants had regular hand to mouth behaviours such as nail biting or smoking. Further details are available on request from the corresponding author.

Sample collection & analysis

24 hr duplicate diet, serum & breast milk

When collecting duplicate food items for the duplicate diet samples, participants were asked not to include water and water based drinks were not included. For tea and coffee, the equivalent portion of milk was added. Samples were collected at the end of the day, homogenized immediately and stored frozen in chemically clean (dichloromethane rinsed) glass jars until analysis. Further details of the duplicate diet sample collection have been published previously (Bramwell et al., 2017). Blood samples were collected in red top vacutainers at the Clinical Research Facility of the Royal Victoria Infirmary in Newcastle. Bloods were left to coagulate for 20 minutes, then centrifuged at 1000 rpm to separate the serum. Laboratory analysis for serum, milk and duplicate diets samples was undertaken by the Food and Environment Research Agency (now Fera Science Ltd.), Sand Hutton, York, UK, and details of the methods used for sample preparation, extraction, clean up and analysis of PBDEs by high resolution gas chromatography - high resolution mass spectroscopy are described elsewhere (Fernandes et al., 2008; Fernandes, 2004).

Indoor and vehicle dust

Dust samples were collected using nylon sample socks with 25 µm mesh size (Allied Filter Fabrics Ltd., Australia) inserted into the nozzle of a Dirt Devil 1100 watt vacuum cleaner. The furniture cleaning attachment was placed over the sock. In workplaces and homes, a 1 m^2 area including carpet and sitting or sleeping area was vacuumed for 2 min, and in the case of wooden or vinyl floors, 4 m^2 for 4 min. Cars were sampled for 2 mins from the driver's seat, the front panels, and the steering wheel. After sampling, socks were closed with a twist tie, sealed in a plastic bag and stored at −18°C. Before and after sampling, the furniture attachment was cleaned thoroughly using a methanol-impregnated disposable wipe. Four field blanks, consisting of 0.2 g sodium sulphate sampled from aluminium foil, collected and treated as samples were taken to ascertain potential interferences from the sampling device.

Briefly, samples were sieved through a 500 µm mesh and homogenised before extraction using pressurised liquid extraction (ASE 300, Dionex). An accurately weighed aliquot (0.1-0.3 g) was placed in a pre-cleaned cell containing 1.5 g florisil and hydromatrix (Varian Inc., UK), and spiked with internal standards $^{13}C_{12}$-BDEs-47, 99, 153 and 209. The ASE cells were extracted with hexane:dichloromethane (1:9, v/v) at 90 °C and 1500 psi. The heating time was 5 minutes, static time 4 min, purge time 90 s, flush volume 50%, with three static cycles. Extracts were concentrated to 0.5 mL using a Zymark Turbovap II then purified by loading onto SPE cartridges filled with ~8 g of

pre-cleaned acidified silica (44% concentrated sulfuric acid, w/w). Analytes were eluted with 25 mL of hexane/dichloromethane (1:1, v/v). The eluate was evaporated to dryness under a gentle stream of nitrogen, then reconstituted in 100 µL of ^{13}C-BDE 100 (25 pg µL^{-1} in methanol) used as a recovery determination (syringe) standard, used to determine the recoveries of internal standards for QA/QC purposes. Penta-BDE (tri to hexa) analyses were conducted on a Fisons MD-800 GC/MS system for which equipment and programming details are provided by Harrad et al. (2008). BDE-209 was analysed by LC–NI-APPI-MS/MS with detailed equipment and programming information previously published by Abdallah et al. (2009).

Additional data from questionnaires and surveys

Average daily portions consumed of meat, fish (including seafood) and dairy were derived for individuals using information from the food frequency questionnaires and seven day food diaries (which included the day of duplicate diet collection). We focussed on meat, fish and dairy portions as the literature indicates these to be the major sources of PBDEs in human diet. Portion counts for the duplicate diets were dichotomised into ≤median and >median and compared with their PBDE concentrations to investigate the relationship between food types and PBDE concentrations in the sample. The average number of meat, fish and dairy portions consumed each day was similarly dichotomised and compared with serum and breast milk PBDE concentrations to determine whether dietary preference indicated higher body burden. Anthropometric indicators of PBDE body burden levels were also investigated e.g. BMI, body fat mass, age, gender, parity and months breastfeeding.

Information on potential PBDE sources in the microenvironments, use of source items, participants' activities and behaviours that might indicate exposure to PBDE was collected via the room surveys, exposure questionnaires and activity diaries. Room surveys collected information such as age and origin for textile floorings (e.g. rugs and carpeting), soft furnishings (e.g. sofas, armchairs, cushions) and electronics (e.g. TVs, computers, gaming and HiFi equipment). Any exposed foam was noted. Normal frequency of vacuuming and dusting, room ventilation information and whether the home was in a rural or urban situation was recorded. Data collected was dichotomised by four methods; (a) has/has not (e.g. exposed foam, suspect soft furnishing (≥20 years old or from the USA), textile flooring ≥20 years of age) (b) urban /rural (c) for numbers of electronic items were split at the median, and (d) split at 'vacuumed twice a week or more and dusted every week or more' for cleaning frequency. Rooms survey items and associated activities were compared with dust PBDE concentrations to investigate indicators of PBDEs in microenvironments. The same factors were also

compared with serum and breast milk PBDE concentrations to determine whether they were indicators of higher PBDE body burden.

Room dust concentrations for repeat sampling weeks

Figure SI1 presents the room dust PBDE concentrations for the couples that repeated the sampling week. Couple 1 changed their main living room between sampling weeks, from a smaller room containing a 1970's sofa and chair to a larger room (~2.5x) with a new sofa and different electronics. Both the magnitude and the pattern of PBDEs in the dust changed to proportionally less BDEs-47,-99 and -100 and more BDE-209. The reduction of Penta-mix congeners could be the reduced influence of the 1970's soft furnishings, the increase in BDE-209 may be from the HiFi equipment from the early 21st Century. A new TV and mattress were introduced to Couple 1's bedroom between sampling weeks however the difference in dust concentrations appears to be mainly an increase in tri-hepta BDE loading in the dust rather than a change in the proportions of congeners that would result from introduction of an item containing PBDE. In contrast, the dust loading of BDE-183 and BDE-209 decreased, suggesting removal of an item. Couple 2's main living area, bedroom and contents of both remained the same between the two sampling weeks. Dust PBDE loading was higher for both tri-hepta BDEs and BDE-209 in the living room in w2, but proportions of congeners appeared similar. Bedroom loading of tri-hepta BDEs was lower in w2 but BDE-209 loading is higher. It is possible that the large BDE-209 increase in the living room may also be influencing bedroom concentrations. The workplace of 2F in the first week was a new building with new furnishings except for printers in 2010. 2M worked from a home office next to the bedroom which contained a USA manufactured office chair labelled as meeting TB117 fire safety requirements. During the repeat sampling week 2F used their home office for breastfeeding and 2M was frequently working away so the room was used somewhat less, possibly the reason for lower tri-hepta BDE loading. However, BDE-209 loading in the home office increased, again possibly the influence of the raised BDE-209 loading in the living area. Both families had one child at w1 and two children at w2 with lots of equipment, toys and floor play, both likely to have an influence in dust PBDE loadings.

Table SI1. Concentrations of PBDEs in living room dust samples (ng/g)

Couple	BDE-17	BDE-28	BDE-47	BDE-49	BDE-66	BDE-85	BDE-99	BDE-100	BDE-153	BDE-154	BDE-183	BDE-209
1(i)*	1.2	4.5	384.6	12.5	13.3	18.2	388.5	76.8	65.3	86.5	13.1	2202
1(ii)*	4.6	9.7	36.3	<0.4	<0.9	1.7	48.9	11.4	38.5	15.1	10.8	13255
2(i)	0.8	0.9	19.6	1.6	1.4	4.6	58.6	24.3	7.4	5.5	12.1	38525
2(ii)	0.9	7.4	41.0	0.9	0.4	0.9	55.9	18.8	54.4	48.2	11.3	106350
3	0.9	2.2	40.0	2.2	2.4	6.6	31.9	9.0	7.9	16.2	7.3	825
4	<0.4	<0.6	5.2	0.4	<0.9	2.8	9.9	4.1	0.8	0.6	<1.7	607
5	1.4	5.9	34.3	<0.4	1.2	2.3	49.6	18.6	28.6	44.4	9.1	23922
6	na	na	na	na	na	na	na	na	na	Na	na	na
7	0.9	1.2	8.1	0.3	1.2	6.7	17.5	6.3	7.3	7.6	4.3	42730
8	8.5	12.1	23.1	8.8	8.0	8.5	45.7	20.1	18.3	13.6	4.7	2958
9	<0.4	<0.6	11.3	<0.4	0.3	1.4	5.9	2.3	<0.7	1.3	10.2	126
10	0.9	6.9	46.2	0.5	<0.9	1.6	57.1	5.8	117.6	55.4	33.5	1245

Key: (i) - 1st sample week, (ii) - 2nd sample week, *participants changed room of main living area (and living area room contents) between sampling weeks, na – not analysed, insufficient sample

Table SI2. Concentrations of PBDEs in bedroom dust samples (ng/g)

Couple	BDE-17	BDE-28	BDE-47	BDE-49	BDE-66	BDE-85	BDE-99	BDE-100	BDE-153	BDE-154	BDE-183	BDE-209
1(i)	0.96	5.56	186.25	2.24	5.39	9.24	187.86	23.60	78.44	58.28	31.56	19,215
1(ii)*	2.29	1.34	272.97	2.28	1.87	10.87	404.57	56.20	67.02	46.80	4.44	2,599
2(i)	6.25	8.03	55.47	12.51	9.74	21.77	161.05	60.30	28.08	<0.6	7.79	3,431
2(ii)	<0.4	<0.6	26.65	0.51	<0.9	0.88	57.57	4.92	14.37	3.14	3.17	7,588
3	0.76	0.98	21.68	1.18	1.29	3.50	6.87	3.68	5.02	2.90	7.64	33.03
4	0.95	2.88	37.97	1.32	<0.9	4.62	47.27	34.64	44.73	43.80	25.66	3,621
5	<0.4	12.41	1,931.09	62.57	34.82	166.42	3,943.14	551.17	310.84	303.52	8.93	107,012
6	0.40	2.04	12.18	1.22	2.01	5.66	16.73	5.14	9.34	3.37	2.35	1,182
7	0.35	<0.6	4.93	0.51	1.11	1.75	7.63	3.44	3.52	2.90	1.98	19,530
8^{+}	0.67	0.86	18.35	<0.4	1.02	2.00	21.56	3.51	10.07	3.90	5.32	1,128
8^{++}	1.22	<0.6	28.56	0.67	1.10	1.03	24.12	1.73	3.51	6.18	4.43	2,789
9	<0.4	<0.6	20.12	0.61	1.35	5.63	28.61	11.99	14.18	4.45	5.36	10,946
10	0.45	0.58	27.02	2.06	2.25	5.14	19.59	14.57	10.52	12.41	7.33	1,762

Key: (i) - 1st sample week, (ii) - 2nd sample week, * new TV introduced, + main house, ++ apartment bedroom

Table SI3. Concentrations of PBDEs in workplace dust samples (ng/g)

Couple	Sex	Notes	BDE-17	BDE-28	BDE-47	BDE-49	BDE-66	BDE-85	BDE-99	BDE-100	BDE-153	BDE-154	BDE-183	BDE-209
1(i)*	M	electronics retail area, office & storage	<0.4	0.95	43.02	<0.4	1.30	6.91	46.47	9.36	17.87	0.46	14.91	1,998
2(i)	F	workplace office	0.58	6.72	12.53	1.63	1.79	5.43	26.86	10.98	5.26	3.79	8.04	1,243
2(ii)	F&M	home office	1.08	12.51	299.03	7.79	2.85	9.86	664.51	22.60	93.03	69.73	7.41	40,022
2(i)	M	home office	<0.4	4.63	416.79	10.56	8.88	27.70	776.22	72.88	84.26	80.81	16.83	7,738
3	F	workplace office	2.84	3.65	5.33	2.48	1.09	4.37	11.02	6.95	8.86	5.59	5.51	806
3	M	work van with work space	<0.4	0.83	16.13	0.85	<0.9	1.85	18.38	1.75	17.54	4.74	367.23	17,088
6	F	workplace	1.49	0.77	20.03	0.46	<0.9	4.72	19.80	14.70	2.49	2.39	2.69	802
6	F	home office	0.99	27.96	11.71	0.42	<0.9	2.43	24.07	1.02	4.48	1.76	4.86	2,474
6	M	hotel	1.16	0.64	2.10	0.65	1.18	3.62	6.07	1.71	5.27	4.62	2.19	728
7	M	hospital	<0.4	1.77	3.74	0.53	<0.9	0.75	5.75	1.47	0.77	<0.6	<1.7	na
10	M	factory office	0.69	3.86	60.60	1.19	9.54	12.68	63.31	16.35	13.97	19.48	18.29	4,951

Key: (i) - 1st sample week, (ii) - 2nd sample week, na – not analysed, sample lost during analysis

Table SI4. Concentrations of PBDEs in vehicle dust samples (ng/g)

Couple	Sex	notes	BDE-17	BDE-28	BDE-47	BDE-49	BDE-66	BDE-85	BDE-99	BDE-100	BDE-153	BDE-154	BDE-183	BDE-209
1(i)	M	train	0.9	1.4	60.8	1.2	1.7	18.8	82.2	31.6	21.1	12.5	2.7	111,406
2(i)	M	car	0.9	1.6	47.5	0.4	1.5	11.3	116.9	8.1	16.3	7.8	19.8	137,426
3	M	work van	<0.4	0.8	16.1	0.8	<0.9	1.8	18.4	1.8	17.5	4.7	367.2	17,088
6	F	car	0.9	1.6	21.5	1.1	<0.9	12.3	36.0	22.1	13.0	9.3	7.0	4,858
6	M	car	2.1	12.6	105.1	1.0	3.2	11.2	344.4	50.4	117.3	23.7	5.9	5,846
7	M	car	<0.4	<0.6	24.5	<0.4	<0.9	2.7	47.6	14.7	1.4	2.9	2.1	315
10	F	car	3.1	4.6	16.8	0.7	3.2	2.7	18.3	7.1	13.2	12.3	6.1	20,876
10	M	car	1.1	0.5	15.8	2.2	2.4	3.1	39.4	21.9	22.4	8.5	8.0	30,338

Key: (i)- 1st sample week, (ii) - 2nd sample week

Table SI5 Summary of room contents and cleaning frequency surveys

	Soft furnishing item count	2001-2008 soft furnishing item count	1991-2000 soft furnishing item count	Pre 1991 soft furnishing item count	Large PUF items or office chairs aged >20 yrs or from USA count	Carpet or rug > 20 years	Crumbling or exposed PUF (No=0, Yes=1)	Electric & electronic item count	2001-2008 electric & electronic item count	1991-2000 electric & electronic item count	Pre 1991 electric & electronic item count	TV count	Computer & laptop count	Large office equipment count	Floor cleaning frequency (daily or more = 0,> weekly but< daily=0.5, weekly=1, < weekly > monthly=1.5, </= monthly=2)	Dusting frequecy (daily or more = 0,> weekly but< daily=0.5, weekly=1, < weekly > monthly=1.5, </= monthly=2)
1 Living room w1	3	0	0	2	2	0	0	4	3	0	0	1	0	0	0.5	1.5
1 Living room w2	6	2	1	0	0	0	0	18	11	4	0	1	0	0	1	1
1 Bedroom w1	4	1	0	0	0	0	0	2	2	0	0	0	0	0	2	2
1 Bedroom w2	4	0	0	0	0	0	0	3	2	0	0	1	1	0	2	2
1M Work w1	6	3	0	0	0	0	0	39	3	0	0	33	1	6	0.5	1
2F Work w1	12	0	0	0	0	0	0	14	8	0	0	0	12	2	1.5	1
2 Living room w1	18	2	3	8	2	1	1	11	4	4	0	0	1	0	0.5	2
2 Living room w2	18	2	3	8	2	1	1	11	4	4	0	0	0	0	0.5	2
2 Bedroom w1	6	5	1	0	0	0	0	2	1	0	0	0	0	0	1	2
2 Bedroom w2	6	5	1	0	0	0	0	2	1	0	0	0	0	0	1	2
2M Home office w1	2	1	0	0	1	0	0	10	5	0	0	0	1	0	0.5	2
2 Home office w2	2	1	0	0	1	0	0	10	5	0	0	0	1	0	0.5	2
3F Work	12	0	0	0	0	0	0	14	9	0	0	0	12	2	1	1
3 Living room	20	4	2	0	0	0	0	7	1	0	0	1	1	0	0	1
3 Bedroom	8	1	0	0	0	0	0	5	2	0	0	1	0	0	0	1
3M Work	10	0	0	0	0	0	1	0	0	0	0	0	0	0	0.5	0.5
4 Living room	12	5	2	0	0	0	0	14	10	0	0	1	2	0	2	2
4 Bedroom	3	1	0	0	0	0	0	3	2	0	1	0	0	0	1.5	1.5
4M Workplace	2	1	0	1	1	1	1	3	1	0	0	0	1	0	1.5	1.5
5 Living room	11	4	0	0	0	1	0	17	6	0	0	1	2	0	1	2
5 Bedroom	12	1	0	0	1	1	0	6	2	0	0	0	0	0	1.5	2
6F Work	28	18	10	0	0	0	0	33	15	0	0	0	20	3	1	1
6F Home office	3	1	1	0	0	0	0	2	1	0	0	0	1	0	1	1.5
6 Living room	9	2	0	0	0	0	0	20	4	0	0	1	4	0	0.5	1
6 Bedroom	8	0	0	0	0	0	0	3	1	0	0	1	0	0	1	1.5
6M Work	2	1	0	0	0	0	0	4	2	0	0	0	1	0	1.5	1
7 Living room	18	12	2	0	0	0	0	19	7	4	2	1	2	0	0.5	2
7 Bedroom	8	6	0	0	0	0	0	2	0	0	0	0	0	0	1	1.5
7M Work	3	3	0	0	0	0	0	12	3	0	0	0	3	1	1	1
8 Bedroom	10	10	0	0	0	0	0	7	1	0	0	0	0	0	1.5	2
8 2nd Living room	2	0	0	0	0	0	0	12	4	0	6	0	1	0	1.5	2
8 2nd bedroom	9	2	0	1	1	0	0	3	0	0	0	0	0	0	1.5	2
9 Living room	18	14	1	2	2	0	0	6	3	1	0	1	1	0	0.5	1.5
9 Bedroom	6	0	2	0	0	0	0	3	1	2	0	1	0	0	0.5	1.5
10 Living room	23	7	0	0	0	0	1	12	4	0	0	1	3	0	0.5	2
10 Bedroom	13	7	0	0	0	0	0	4	2	0	0	1	0	0	1.5	1.5
10M Work	1	0	0	0	1?	0	0	3	0	0	0	0	2	0	0.5	2

Table SI6 Spearman's rho and correlation coefficients for PBDE concentrations in indoor dusts and room survey information (ng/g)

Room Survey Information		Median bound Indoor dust concentrations (ng/g) (n=33)							
		BDE47	BDE99	BDE100	BDE153	BDE154	BDE183	BDE209	$\sum BDE_{3\_7}$
Soft furnishing item count	Correlation Coefficient	-.034	-.211	-.166	-.172	-.013	.064	-.076	-.223
	Sig. (2-tailed)	.850	.239	.357	.337	.943	.724	.679	.212
2001-2008 soft furnishing item count	Correlation Coefficient	.041	-.120	-.219	-.174	-.138	-.080	.027	-.308
	Sig. (2-tailed)	.823	.507	.220	.332	.444	.658	.883	.081
1991-2000 soft furnishing item count	Correlation Coefficient	.055	.031	-.028	-.130	-.128	-.170	.151	-.194
	Sig. (2-tailed)	.760	.863	.876	.470	.479	.345	.409	.279
Pre 1991 soft furnishing item count	Correlation Coefficient	.119	.059	.050	-.019	.051	.171	.100	.080
	Sig. (2-tailed)	.508	.746	.784	.916	.779	.342	.585	.657
Carpet or rug >20 years of age	Correlation Coefficient	.351*	.322	.332	.273	.351*	.205	.532**	.254
	Sig. (2-tailed)	.045	.068	.059	.124	.045	.253	.002	.155
Large PUF items or office chairs aged >20 yrs or from USA count	Correlation Coefficient	.372*	.354*	.300	.252	.318	.332	.297	.366*
	Sig. (2-tailed)	.036	.047	.095	.163	.076	.063	.105	.039
Crumbling or exposed PUF (No=0, Yes=1)	Correlation Coefficient	.107	0.000	-.137	.215	.185	.410*	.266	.234
	Sig. (2-tailed)	.552	1.000	.449	.231	.302	.018	.141	.190
Electric & electronic item count	Correlation Coefficient	.005	-.027	.039	-.077	.112	-.120	-.040	-.159
	Sig. (2-tailed)	.978	.883	.827	.672	.534	.506	.827	.376
2001-2008 electric & electronic item count	Correlation Coefficient	.107	.083	.229	.084	.241	-.060	.001	.006
	Sig. (2-tailed)	.554	.645	.199	.643	.177	.741	.997	.972
1991-2000 electric & electronic item count	Correlation Coefficient	.140	.026	.050	-.011	.114	.039	.359*	-.105
	Sig. (2-tailed)	.436	.884	.782	.953	.527	.831	.044	.562
Pre 1991 electric & electronic item count	Correlation Coefficient	-.102	-.098	.074	.008	.165	-.067	.167	.008
	Sig. (2-tailed)	.574	.587	.682	.966	.358	.710	.362	.966
TV count	Correlation Coefficient	-.058	-.176	-.137	-.068	-.034	-.082	-.369*	-.121
	Sig. (2-tailed)	.750	.328	.447	.707	.849	.651	.038	.503
Computer & laptop count	Correlation Coefficient	-.230	-.200	-.226	-.280	-.059	-.362*	-.254	-.244
	Sig. (2-tailed)	.197	.266	.206	.114	.745	.039	.161	.172
Large office equipment count	Correlation Coefficient	-.319	-.259	-.165	-.308	-.417*	-.206	-.293	-.277
	Sig. (2-tailed)	.070	.145	.358	.081	.016	.250	.104	.119
Floor cleaning frequency (daily or more = 0, >weekly but< daily = 0.5, weekly = 1, > weekly but < monthly = 1.5, </= monthly=2)	Correlation Coefficient	-.105	.017	.197	.021	-.002	-.239	-.056	-.066
	Sig. (2-tailed)	.562	.925	.272	.909	.991	.181	.763	.714
Dusting frequecy (daily or more = 0, >weekly but< daily = 0.5, weekly = 1, > weekly but < monthly = 1.5, </= monthly=2)	Correlation Coefficient	.546**	.555**	.421*	.480**	.494**	.079	.481**	.404*
	Sig. (2-tailed)	.001	.001	.015	.005	.004	.661	.005	.020

Notes: ** Correlation is significant at the 0.01 level (2-tailed), * Correlation is significant at the 0.05 level (2-tailed), Non-significant correlations (<0.1) (2-tailed)

Table SI7 Spearmans rho and correlation coefficients for PBDE concentrations in matched body burden (serum and breast milk) and indoor dust data (ng/g)

			Serum (ng/g lw) MB						Breast milk (ng/g lw) MB					
			BDE-47	BDE-99	BDE-153	∑BDE-47_99_100_153	BDE-183	BDE-209	BDE-47	BDE-99	BDE-153	∑BDE-47_99_100_153	BDE-183	BDE-209
Bedroom dust (ng/g) MB, 24 matched serum and 6 matched breast milk	BDE-47	Correlation Coefficient	.361	.375	.335	.380	.202	.357	-.086	-.257	.143	.429	-.143	.429
		Sig. (2-tailed)	.083	.071	.110	.067	.343	.086	.872	.623	.787	.397	.787	.397
	BDE-99	Correlation Coefficient	.312	.291	.342	.340	.192	.361	-.086	-.143	.143	.257	-.543	.714
		Sig. (2-tailed)	.138	.167	.102	.104	.369	.083	.872	.787	.787	.623	.266	.111
	BDE-153	Correlation Coefficient	.446*	.452*	.385	.452*	.265	.408*	-.257	-.257	-.029	.143	-.486	.600
		Sig. (2-tailed)	.029	.027	.063	.027	.211	.048	.623	.623	.957	.787	.329	.208
	$\sum BDE_{3-7}$	Correlation Coefficient	.392	.392	.392	.418*	.248	.389	-.257	-.257	-.029	.143	-.486	.600
		Sig. (2-tailed)	.058	.058	.058	.042	.243	.060	.623	.623	.957	.787	.329	.208
	BDE-183	Correlation Coefficient	.282	.485*	.260	.359	.188	.120	-.714	-.657	-.029	-.371	.086	-.257
		Sig. (2-tailed)	.181	.016	.220	.085	.378	.575	.111	.156	.957	.468	.872	.623
	BDE-209	Correlation Coefficient	.160	.223	.099	.199	-.033	.016	-.600	-.314	.314	-.429	-.371	.543
		Sig. (2-tailed)	.454	.294	.647	.352	.878	.942	.208	.544	.544	.397	.468	.266
Living room dust (ng/g) MB 22 matched serum and 6 matched breast milk	BDE-47	Correlation Coefficient	.261	.120	.003	.102	.143	.344	.771	.371	.543	.714	.257	.029
		Sig. (2-tailed)	.242	.595	.988	.652	.526	.117	.072	.468	.266	.111	.623	.957
	BDE-99	Correlation Coefficient	.084	.041	.093	.070	.154	.283	.429	-.086	.657	.543	.029	-.086
		Sig. (2-tailed)	.711	.857	.681	.756	.494	.202	.397	.872	.156	.266	.957	.872
	BDE-153	Correlation Coefficient	.267	.116	.014	.109	.168	.421	.657	.143	.429	.657	.086	-.143
		Sig. (2-tailed)	.229	.609	.952	.630	.456	.051	.156	.787	.397	.156	.872	.787
	$\sum BDE_{3-7}$	Correlation Coefficient	.258	.106	.061	.125	.181	.437*	.657	.143	.429	.657	.086	-.143
		Sig. (2-tailed)	.246	.637	.787	.581	.420	.042	.156	.787	.397	.156	.872	.787
	BDE-183	Correlation Coefficient	.358	.288	.250	.306	.279	.424*	.829*	.543	.371	.600	.371	-.086
		Sig. (2-tailed)	.102	.194	.261	.166	.209	.049	.042	.266	.468	.208	.468	.872
	BDE-209	Correlation Coefficient	-.407	-.514*	-.199	-.345	-.256	-.060	.257	-.143	.486	.429	-.543	.371
		Sig. (2-tailed)	.060	.014	.375	.116	.250	.791	.623	.787	.329	.397	.266	.468
All workplace dusts dust (ng/g) MB 11 matched serum	BDE-47	Correlation Coefficient	0.565	0.424	0.328	0.018	0.342	.724*						
		Sig. (2-tailed)	0.070	0.194	0.325	0.958	0.304	0.012						
	BDE-99	Correlation Coefficient	.656*	0.533	0.355	-0.009	0.342	.779**						
		Sig. (2-tailed)	0.028	0.091	0.284	0.979	0.304	0.005						
	BDE-153	Correlation Coefficient	0.510	0.478	0.374	0.155	0.305	.724*						
		Sig. (2-tailed)	0.109	0.137	0.258	0.649	0.361	0.012						
	$\sum BDE_{3-7}$	Correlation Coefficient	0.418	0.309	0.000	0.509	-0.082	0.491						
		Sig. (2-tailed)	0.201	0.355	1.000	0.110	0.811	0.125						
	BDE-183	Correlation Coefficient	0.465	.651*	0.474	0.273	0.369	.651*						
		Sig. (2-tailed)	0.150	0.030	0.141	0.416	0.264	0.030						
	BDE-209[a]	Correlation Coefficient	0.383	0.353	0.219	0.182	0.201	.717*						
		Sig. (2-tailed)	0.275	0.318	0.544	0.614	0.578	0.020						
Vehicle dust (ng/g) MB 9 matched serums	BDE-47	Correlation Coefficient	-0.085	-0.220	0.390	-0.305	0.441	-0.068						
		Sig. (2-tailed)	0.828	0.569	0.300	0.425	0.235	0.862						
	BDE-99	Correlation Coefficient	-0.322	-0.373	0.237	-0.559	0.373	-0.203						
		Sig. (2-tailed)	0.398	0.323	0.539	0.117	0.323	0.600						
	BDE-153	Correlation Coefficient	0.068	-0.034	0.525	-0.186	0.525	0.034						
		Sig. (2-tailed)	0.862	0.931	0.146	0.631	0.146	0.931						
	$\sum BDE_{3-7}$	Correlation Coefficient	-0.025	-0.084	0.427	-0.142	0.427	-0.025						
		Sig. (2-tailed)	0.949	0.831	0.252	0.715	0.252	0.949						
	BDE-183	Correlation Coefficient	-0.153	-0.034	0.356	-0.356	0.186	-0.051						
		Sig. (2-tailed)	0.695	0.931	0.347	0.347	0.631	0.897						
	BDE-209[a]	Correlation Coefficient	0.017	0.170	0.390	-0.153	0.153	0.153						
		Sig. (2-tailed)	0.965	0.663	0.300	0.695	0.695	0.695						

Notes: ** Correlation is significant at the 0.01 level (2-tailed), * Correlation is significant at the 0.05 level (2-tailed), Non-significant correlations (<0.1) (2-tailed), $\sum BDE_{3-7}$ = Sum tri-hepta BDEs, [a] BDE-209 for 6M was lost during extraction

Table SI8 Spearman's rho and correlation coefficients for PBDE concentrations in matched serum and breast milk data and serum/breastmilk PBDE concentration ratios

Breastmilk (n=6)		BDE28	BDE47	BDE99	BDE153	BDE209
BDE28	Correlation	-.086	.314	-.200	-.371	.943**
	Sig. (2-tailed)	.872	.544	.704	.468	.005
BDE47	Correlation	-.086	.314	-.200	-.371	.943**
	Sig. (2-tailed)	.872	.544	.704	.468	.005
BDE99	Correlation	.086	.657	.143	.029	.771
	Sig. (2-tailed)	.872	.156	.787	.957	.072
BDE153	Correlation	.371	.086	.257	.314	.029
	Sig. (2-tailed)	.468	.872	.623	.544	.957
BDE209	Correlation	-.086	.200	.029	.257	.257
	Sig. (2-tailed)	.872	.704	.957	.623	.623
Serum/ breastmilk concentration ratio	**Median**	2.2	1.3	3.1	0.4	6.0
	Mean	1.6	0.7	3.0	0.3	6.1

Notes: ** Correlation is significant at the 0.01 level (2-tailed), Non-significant correlations (<0.1) (2-tailed),

Table SI9 Spearman's rho and correlation coefficients for PBDE concentrations in serum and breast milk with the duplicate diet sample collected during the 24 hours prior to body burden sampling, food type portion numbers for the 24 hours and 7 days prior to body burden sampling and food frequency data examining longer term dietary exposures.

			Serum PBDE concentrations (n=24)					Breastmilk PBDE Concentrations (n=6)				
			BDE-47	BDE-99	BDE-153	$\sum BDE_{3-7}$	BDE-209	BDE-47	BDE-99	BDE-153	$\sum BDE_{3-7}$	BDE-209
24 h Duplicate diet PBDE concentrations	BDE-47	Correlation Coefficient	-.040	-.082	.061	-.172	.113	.200	.429	-.029	.371	.886*
		Sig. (2-tailed)	.853	.704	.777	.421	.599	.704	.397	.957	.468	.019
	BDE-99	Correlation Coefficient	-.296	-.199	-.136	-.293	-.243	-.200	.086	.029	.143	.829*
		Sig. (2-tailed)	.161	.351	.527	.165	.253	.704	.872	.957	.787	.042
	BDE-153	Correlation Coefficient	-.263	-.175	-.279	.042	-.230	.143	.086	-.086	.371	.657
		Sig. (2-tailed)	.214	.414	.187	.846	.279	.787	.872	.872	.468	.156
	∑BDE3-7	Correlation Coefficient	-.027	.051	-.228	.407*	-.058	.029	-.257	.714	-.029	-.143
		Sig. (2-tailed)	.900	.812	.283	.048	.787	.957	.623	.111	.957	.787
	BDE-209	Correlation Coefficient	.023	.137	-.136	.346	-.217	-1.000**	-.829*	-.086	-.829*	-.200
		Sig. (2-tailed)	.913	.522	.526	.098	.308		.042	.872	.042	.704
Portion numbers for 24 hours prior to body burden sampling (n=24)	Meat	Correlation Coefficient	-.014	.099	.151	.156	-.025	.353	.441	0.000	-.088	-.441
		Sig. (2-tailed)	.949	.647	.480	.466	.907	.492	.381	1.000	.868	.381
	Fish and Seafood	Correlation Coefficient	-.037	-.245	-.111	-.141	.111	.655	.655	-.393	.655	.393
		Sig. (2-tailed)	.864	.249	.605	.512	.605	.158	.158	.441	.158	.441
	Dairy	Correlation Coefficient	-.156	-.270	-.106	-.182	.009	-.062	-.123	-.679	-.216	-.093
		Sig. (2-tailed)	.466	.202	.621	.393	.966	.908	.816	.138	.681	.862
Portion numbers for 7 days prior to body burden samples (n=24)	Meat	Correlation Coefficient	.337	.495*	.441*	.426*	-.044	.029	.348	-.319	-.232	-.406
		Sig. (2-tailed)	.107	.014	.031	.038	.838	.957	.499	.538	.658	.425
	Fish and Seafood	Correlation Coefficient	-.063	-.007	-.096	-.006	-.158	.120	.239	-.837*	0.000	-.359
		Sig. (2-tailed)	.771	.974	.655	.979	.462	.822	.648	.038	1.000	.485
	Dairy	Correlation Coefficient	-.452*	-.349	-.090	-.361	-.434*	-.257	-.086	-.029	.200	.600
		Sig. (2-tailed)	.026	.095	.676	.083	.034	.623	.872	.957	.704	.208
	Processed meats e.g.pies & bacon	Correlation Coefficient	.397	.432*	.321	.362	.080	-.203	-.116	-.551	-.348	-.754
		Sig. (2-tailed)	.055	.035	.127	.082	.710	.700	.827	.257	.499	.084
	Oily fish	Correlation Coefficient	.059	.207	.073	.189	-.133	-.463	-.309	-.463	-.617	-.772
		Sig. (2-tailed)	.783	.332	.734	.378	.536	.355	.552	.355	.192	.072
	White fish	Correlation Coefficient	-.449*	-.309	-.016	-.253	-.244	.655	.655	-.393	.655	.393
		Sig. (2-tailed)	.028	.142	.939	.232	.250	.158	.158	.441	.158	.441
	Other Seafood	Correlation Coefficient	.490*	.427*	.114	.362	.306	.265	.383	-.794	.147	-.235
		Sig. (2-tailed)	.015	.037	.595	.082	.146	.612	.454	.059	.781	.653
	Dairy products e.g. yoghurt, cheese or milk puddings	Correlation Coefficient	-.371	-.478*	-.209	-.361	-.206	.414	.828*	-.414	.207	.414
		Sig. (2-tailed)	.075	.018	.326	.083	.335	.414	.042	.414	.694	.414
Portion numbers per week derived from Food frequency questionaire for longer term eating habits (n=24)	Meat	Correlation Coefficient	.146	.227	.305	.311	.093	.257	.257	.029	-.143	-.600
		Sig. (2-tailed)	.495	.286	.148	.139	.666	.623	.623	.957	.787	.208
	Fish and Seafood	Correlation Coefficient	-.071	-.005	-.055	.017	-.050	-.493	-.319	-.493	-.783	-.812*
		Sig. (2-tailed)	.741	.980	.798	.937	.816	.321	.538	.321	.066	.050
	Dairy	Correlation Coefficient	-.352	-.340	-.322	-.336	-.292	-.493	-.174	-.841*	-.754	-.319
		Sig. (2-tailed)	.091	.104	.125	.108	.166	.321	.742	.036	.084	.538
	Offal	Correlation Coefficient	.371	.468*	.234	.404	.291	-.655	-.655	-.655	-.655	-.655
		Sig. (2-tailed)	.074	.021	.271	.050	.168	.158	.158	.158	.158	.158
	Processed meats e.g. pies & bacon	Correlation Coefficient	.227	.305	.180	.298	-.012	.118	.235	-.118	-.294	-.618
		Sig. (2-tailed)	.287	.147	.400	.157	.955	.824	.653	.824	.571	.191
	Eats the fat from the meat	Correlation Coefficient	.223	.307	.272	.269	.045	-.093	.062	-.463	-.432	-.772
		Sig. (2-tailed)	.296	.145	.198	.203	.836	.862	.908	.355	.392	.072
	Oily fish	Correlation Coefficient	.029	.065	-.024	.102	-.031	-.530	-.441	-.530	-.883*	-.794
		Sig. (2-tailed)	.894	.762	.912	.635	.886	.280	.381	.280	.020	.059
	White fish	Correlation Coefficient	-.025	.105	.122	.108	.094	-.463	-.309	-.463	-.617	-.772
		Sig. (2-tailed)	.906	.624	.571	.614	.662	.355	.552	.355	.192	.072
	Other Seafood	Correlation Coefficient	.008	.021	-.188	-.030	-.173	-.293	-.098	-.293	-.488	-.683
		Sig. (2-tailed)	.970	.921	.380	.889	.419	.573	.854	.573	.326	.135
	Ice-cream	Correlation Coefficient	-.207	-.058	.035	-.013	-.102	-.414	-.828*	.414	-.207	-.414
		Sig. (2-tailed)	.332	.789	.872	.950	.636	.414	.042	.414	.694	.414
	Dairy products e.g. yoghurt, cheese or milk puddings	Correlation Coefficient	-.533**	-.506*	-.386	-.437*	-.177	-.429	-.600	-.200	-.429	-.086
		Sig. (2-tailed)	.007	.012	.062	.033	.408	.397	.208	.704	.397	.872
	Eats normal fat dairy products rather than reduced fat products	Correlation Coefficient	-.252	-.139	-.170	-.194	-.132	-.600	-.600	-.371	-.314	.086
		Sig. (2-tailed)	.234	.517	.427	.363	.537	.208	.208	.468	.544	.872

Notes: ** Correlation is significant at the 0.01 level (2-tailed), * Correlation is significant at the 0.05 level (2-tailed), Non-significant correlations (<0.1) (2-tailed), $\sum BDE_{3-7}$ = Sum tri-hepta BDEs

Table SI10 Spearman's rho and correlation coefficients for PBDE concentrations in serum and breast milk with anthropometrics and selected data from exposure questionnaires and seven day activity diaries.

		Serum PBDE (n=24)					Milk PBDE (n=6)				
		BDE47	BDE99	BDE153	BDE209	sumBDE$_{3-7}$	BDE47	BDE99	BDE153	BDE209	sumBDE$_{3-7}$
Gender	Correlation	-.036	-.265	-.596**	-.120	-.060					
	Sig. (2-tailed)	.867	.211	.002	.575	.780					
Age	Correlation	-.518**	-.395	-.265	-.441*	-.197	.232	.609	-.696	-.029	-.203
	Sig. (2-tailed)	.010	.056	.211	.031	.356	.658	.200	.125	.957	.700
Body Mass Index (BMI) (weight/height)	Correlation	-.074	-.112	-.390	-.154	.023	.314	.600	-.600	.314	.029
	Sig. (2-tailed)	.731	.602	.060	.471	.916	.544	.208	.208	.544	.957
% Body fat	Correlation	.056	-.153	-.492*	-.041	-.001	.257	.600	-.200	.771	.257
	Sig. (2-tailed)	.796	.475	.015	.850	.997	.623	.208	.704	.072	.623
Main residence location (rural=0, urban=1)	Correlation	.026	-.166	-.057	.140	-.153	0.000	.207	-.828*	-.207	-.414
	Sig. (2-tailed)	.906	.438	.790	.513	.475	1.000	.694	.042	.694	.414
Time outdoors (h/day)	Correlation	-.027	.219	.023	-.197	.157	-.657	-.600	.257	.029	-.200
	Sig. (2-tailed)	.899	.303	.916	.355	.465	.156	.208	.623	.957	.704
Time on computer or gaming (h/day)	Correlation	-.356	-.304	-.308	-.304	-.158	.058	-.145	.522	.348	.580
	Sig. (2-tailed)	.088	.149	.144	.149	.460	.913	.784	.288	.499	.228
Time watching TV (h/day)	Correlation	-.016	.094	.009	-.380	.342	-.348	-.116	-.696	-.029	-.203
	Sig. (2-tailed)	.940	.661	.968	.067	.101	.499	.827	.125	.957	.700
Time in vehicle (h/day)	Correlation	-.055	.059	.077	-.139	.238	.232	-.029	.464	.116	.638
	Sig. (2-tailed)	.800	.784	.722	.517	.263	.658	.957	.354	.827	.173
Hand to mouth behaviour y=1	Correlation	-.099	-.192	-.086	-.113	-.060	.414	0.000	.414	-.414	.207
	Sig. (2-tailed)	.644	.369	.689	.600	.782	.414	1.000	.414	.414	.694
Months breast fed as baby	Correlation	.308	.082	.174	.325	-.258	.432	.093	.432	.339	.833*
	Sig. (2-tailed)	.143	.703	.417	.121	.224	.392	.862	.392	.510	.039
Work or hobby with electronics y=1	Correlation	.332	.383	.594**	.332	.051	.393	.131	.393	-.393	.393
	Sig. (2-tailed)	.113	.065	.002	.113	.813	.441	.805	.441	.441	.441
Work or hobby with foam or fabic activity y=1	Correlation	.178	.388	.291	-.065	.275	-.131	.393	-.131	.131	-.393
	Sig. (2-tailed)	.406	.061	.168	.764	.194	.805	.441	.805	.805	.441
Regular public transport y=1	Correlation	-.089	-.192	-.166	0.000	.102	-.414	-.621	-.414	-.621	-.621
	Sig. (2-tailed)	.678	.370	.438	1.000	.635	.414	.188	.414	.188	.188
Number of short haul flights per year	Correlation	.364	.237	.243	.388	-.035	.736	.500	.265	-.265	.412
	Sig. (2-tailed)	.080	.265	.253	.061	.870	.096	.312	.612	.612	.417
Number of long haul flights per year	Correlation	.106	.218	.163	.015	.307	0.000	.207	0.000	0.000	-.414
	Sig. (2-tailed)	.623	.307	.446	.946	.144	1.000	.694	1.000	1.000	.414
Smoking: current=2, historic =1, never=0	Correlation	-.087	-.147	-.212	-.059	-.328	.488	.683	-.293	.293	.098
	Sig. (2-tailed)	.686	.494	.321	.784	.117	.326	.135	.573	.573	.854
Women only data											
Parity	Correlation	-.289	-.430	-.571	-.095	.171	.098	-.098	-.683	-.293	-.098
	Sig. (2-tailed)	.361	.163	.052	.768	.594	.854	.854	.135	.573	.854
Total months breastfeeding	Correlation	-.259	-.315	-.441	-.063	.126	-.143	-.371	-.600	-.257	-.086
	Sig. (2-tailed)	.416	.318	.151	.846	.696	.787	.468	.208	.623	.872
Current month of breastfeeding	Correlation	-.778*	-.503	-.587	-.228	-.383	-.319	-.696	.609	.116	.029
	Sig. (2-tailed)	.023	.204	.126	.588	.349	.538	.125	.200	.827	.957

Notes: ** Correlation is significant at the 0.01 level (2-tailed), * Correlation is significant at the 0.05 level (2-tailed), Non-significant correlations (<0.1) (2-tailed), sum BDE$_{3-7}$ = Sum tri-hepta BDEs

Table SI11. Personal daily exposure (pg kg^{-1} bw day^{-1}) to selected PBDEs via ingestion of dust from all sampled microenvironments and diet.

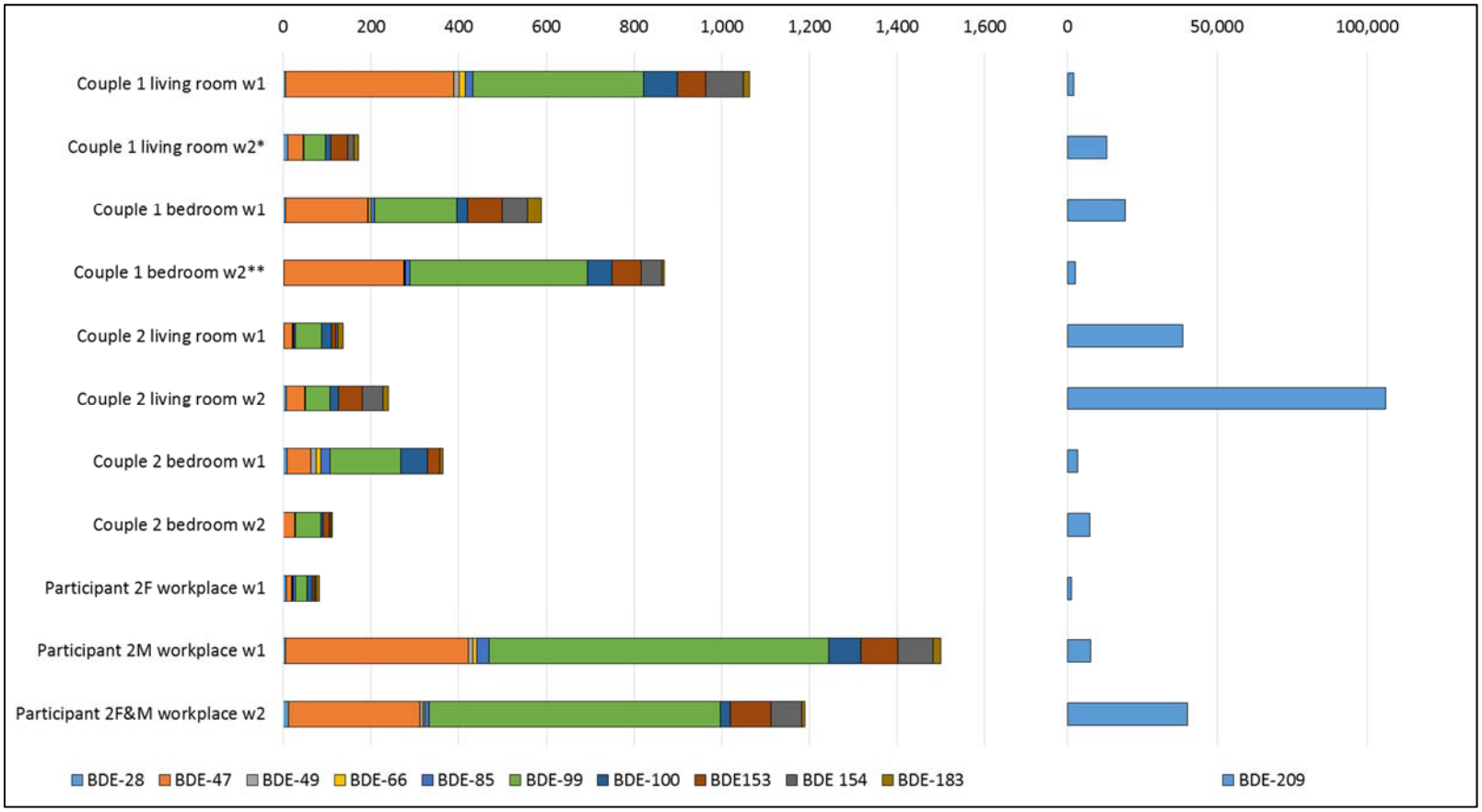
Participant	Exposure under mean dust intake scenario						Exposure under high dust intake scenario						PBDE exposure determined from 24 h duplicate diet					
	Dust BDE-47	Dust BDE-99	Dust BDE-153	Dust BDE-183	Dust BDE-209	Dust Σtri-hepta BDEs	Dust BDE-47	Dust BDE-99	Dust BDE-153	Dust BDE-183	Dust BDE-209	Dust Σtri-hepta	DD BDE-47	DD BDE-99	DD BDE-153	DD BDE-183	DD BDE-209	DD Σtri-hepta BDEs
1Fi	51.20	51.86	15.18	5.06	2.835	155	128.01	129.66	37.94	12.65	7.086	388	203	256	22.9	10.2	787	601
1Fii	36.25	53.05	12.13	1.73	1.872	125	90.62	132.63	30.33	4.32	4.679	314	785	100	44.0	9.2	3	1315
1Mi	24.83	27.00	10.28	3.94	3.068	87	62.07	67.51	25.70	9.84	7.670	217	163	199	20.8	8.3	1861	473
1Mii	40.78	59.63	13.72	1.96	2.078	141	101.95	149.07	34.30	4.90	5.195	352	443	70	8.4	7.3	1	776
2Fi	8.60	22.04	3.96	1.93	2.913	53	21.50	55.09	9.90	4.83	7.284	133	87	100	29.1	28.3	600	466
2Fii	-	-	-	-	-	-	-	-	-	-	-	-	122	120	31.4	5.7		328
2Mi	24.96	54.44	7.79	2.70	4.848	117	62.40	136.10	19.47	6.75	12.119	293	58	65	8.3	1.9	292	155
2Mii	-	-	-	-	-	-	-	-	-	-	-	-	96	107	18.3	4.6		270
3F	7.62	5.84	2.98	2.25	692	30	19.06	14.60	7.44	5.63	1.731	76	29	31	6.2	3.7	505	86
3M	6.63	4.81	2.61	22.00	1.212	43	16.57	12.01	6.52	55.00	3.031	108	29	31	5.4	2.9	557	85
4F	6.39	8.13	6.79	3.58	945	41	15.97	20.32	16.97	8.94	2.363	103	69	82	23.0	10.2	1229	228
4M	5.32	6.80	5.69	3.06	750	34	13.29	17.01	14.24	7.66	1.875	86	192	69	14.1	9.4	417	480
5F	264	538	43.92	1.76	15851	1.007	660	1346	109.81	4.40	39.627	2.517	113	147	41.7	23.9	1134	430
5M	172	349	29.65	1.54	11056	659	429	872	74.12	3.86	27.639	1.646	173	260	54.6	18.2	846	647
6F	3.56	5.00	1.96	0.86	543	19	8.90	12.49	4.91	2.14	1.358	48	47	39	8.7	4.7	1055	124
6M	5.69	12.85	5.54	0.83	795	36	14.23	32.13	13.86	2.07	1.987	90	43	48	7.0	3.0	396	125
7F	2.32	3.43	1.94	0.80	5.423	16	5.79	8.58	4.84	2.00	13.556	39	51	60	10.4	11.7	29	161
7M	2.60	4.01	1.86	0.80	5.134	16	6.49	10.03	4.66	2.01	12.836	41	62	80	22.1	12.3	205	216
8F	6.57	7.93	4.25	1.68	1.225	32	16.44	19.83	10.63	4.21	3.062	80	119	117	34.3	21.1	1319	367
8M	3.53	4.15	2.02	1.01	281	14	8.83	10.38	5.06	2.53	702	35	208	211	49.0	18.6	1688	588
9F	4.52	5.14	2.43	2.00	1.642	20	11.31	12.85	6.07	5.01	4.105	50	94	91	14.7	13.4	668	257
9M	5.48	6.26	3.82	1.92	1.784	31	13.69	15.64	9.55	4.79	4.459	78	25	24	5.7	3.6	220	73
10F	9.25	9.35	12.95	4.34	1.044	52	23.12	23.37	32.37	10.85	2.609	130	55	56	12.9	24.2	408	176
10M	7.51	8.72	6.89	3.09	1.971	37	18.77	21.80	17.23	7.72	4.929	92	23	24	6.7	26.9	276	95
Mean	31.80	56.70	9.02	3.13	3.089	125.73	79.49	141.74	22.54	7.82	7.723	314	137	100	21	12	659	355
P50	7.07	8.42	5.62	1.95	1.828	39.06	17.67	21.06	14.05	4.86	4.569	98	90	81	17	10	531	264
Max	264.19	538.20	43.92	22.00	15.851	1.007	660.49	1.346	109.81	55.00	39.627	2.517	785	260	55	28	1.861	1.315
UK[1]	16	26	4.4	-	61.000	53	-	-	-	-	871.000	771	-	-	-	-	-	-
UK[2]													200	140	30		2560	
UK[3]													410	250	60		5030	
DE[4]	7.5	10.4	2.3	3.6	260	32.6	46.90	82	9.40	18.40	520	128.3	161	255	51	505	260	1194
DE[5]	-	-	-	-	-	-	-	-	-	-	-	-	340	501	140	1367	520	2496
BE[6]	-	-	-	-	57	5	-	-	-	-	143	13	-	-	-	-	1583	167
BE[7]	-	-	-	-	183	23	-	-	-	-	483	58	-	-	-	-	3967	367
USA[8]					371	471					2.140	7.290						

Notes: [1] Abdallah and Harrad (2014) & Harrad et al. (2008) for 70 kg bw mean, [2] UK FSA TDS 2012 mean upper bound (UB) data (Mortimer, 2013), [3] UK FSA TDS 2012 P97.5 upper bound data (Mortimer, 2013), [4] Fromme et al. (2009) mean, adult 60 kg bw, [5] Fromme et al. (2009) mean, [6] Roosens et al. (2009) mean, adult 60 kg bw, [7] Roosens et al. (2009) maximum, adult 60 kg bw, [8] Harrad et al. (2008)

Table SI12. Summary of adult (using average and high dust intake scenarios and duplicate diet data from this study) and infant (using average and high dust intake scenarios from this study and average and high dietary intake estimates from the UK FSA TDS 2011) PBDE intakes and associated Margins of Exposure (MOEs) with US-EPA health reference values

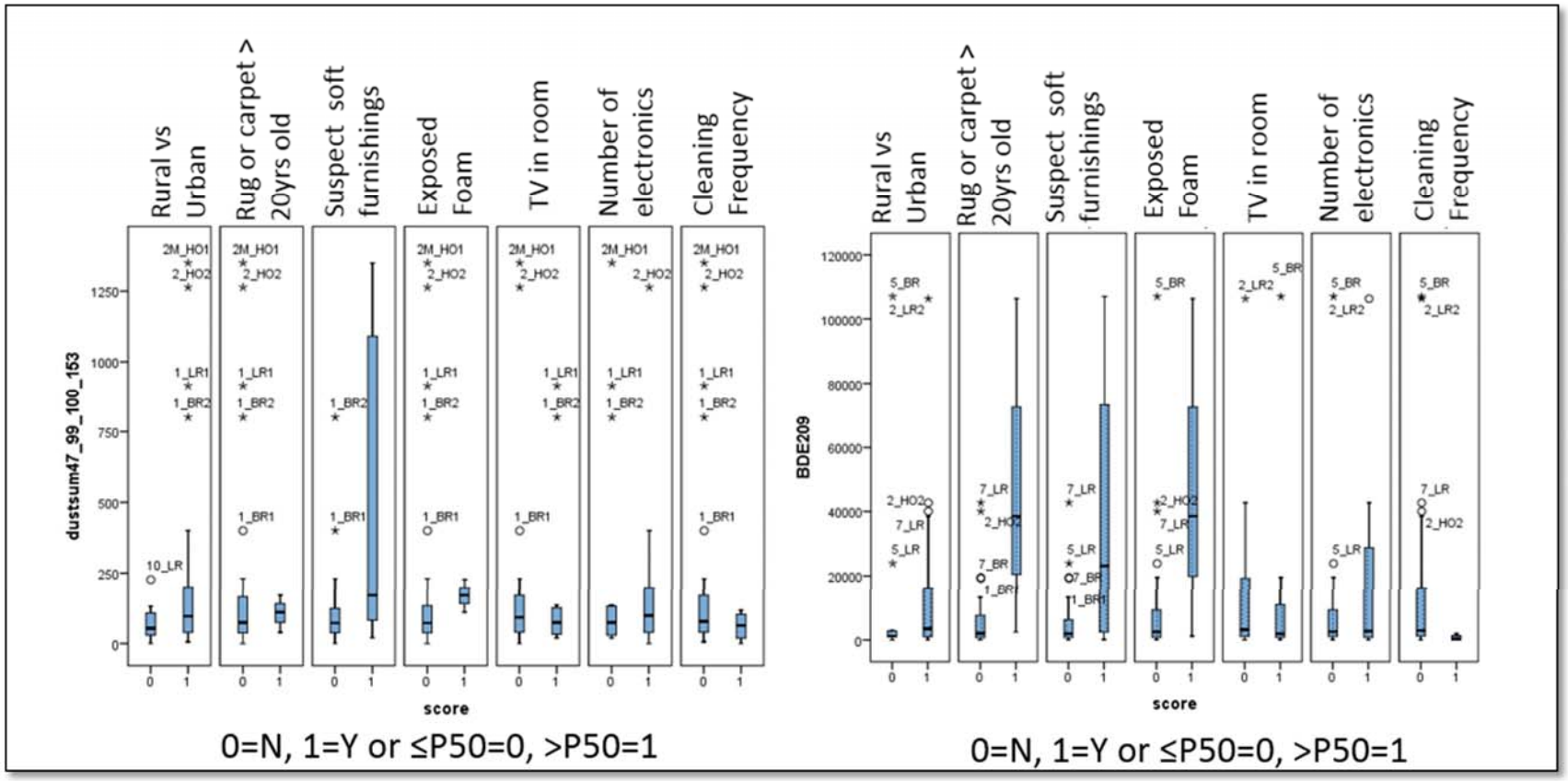
	BDE-47	BDE-99	BDE-153	BDE-209	BDE-47	BDE-99	BDE-153	BDE-209	BDE-47	BDE-99	BDE-153	BDE-209	BDE-47	BDE-99	BDE-153	BDE-209
Total PBDE Intake (pg/kg bw/day)	**Sum adult mean dust intake +DD**				**Sum adult high dust intake +DD**				**Sum infant average dust intake + average TDS**				**Sum infant high dust intake + P97.5 TDS**			
Mean	171	155	29	3,748	219	240	43	8,382	683	610	121	16,289	1,511	1,430	283	44,527
Min	30	30	8	1,167	39	40	12	2,236	610	480	100	9,210	1,220	910	200	16,210
Median	89	93	23	2,211	106	103	34	4,727	627	500	112	13,492	1,286	990	249	33,338
Max	822	685	86	16,985	876	1493	151	40,762	1,270	1,826	210	48,837	3,862	6,292	639	174,720
US EPA RfDs for PBDEs (ng/kg bw/day) (2014)	**100**	**100**	**200**	**7,000**	**100**	**100**	**200**	**7,000**	**100**	**100**	**200**	**7,000**	**100**	**100**	**200**	**7,000**
	(EPA) Adult mean MOEs				**(EPA) Adult high MOEs**				**(EPA) Infant mean MOEs**				**(EPA) Infant high MOEs**			
Mean	1,331	1,315	10,676	3,066	1,099	1,060	7,380	1,567	150	180	1,681	486	71	87	742	204
Min	122	146	2,337	412	114	67	1,320	172	79	55	953	143	26	16	313	40
Median	1,130	1,076	8,692	3,167	940	971	6,089	1,481	159	200	1,754	508	77	101	781	203
Max	3,293	3,286	25,123	5,997	2,592	2,511	16,843	3,130	162	205	1,911	706	80	106	915	368

Figure SI1. Comparison of room dust tri-hepta BDE and BDE-209 concentrations in Week 1 (w1) and Week 2 (w2) for Couples 1 and 2 who repeated the sampling week (ng g^{-1})



* Participants changed main living area room and contents, ** new TV introduced

Figure SI2. Indicators of ∑BDEs 47, 99, 100 and 153, and BDE-209 concentrations in room dust



Note: Data is dichotomised by four methods; (a) has/has not (e.g. exposed foam, suspect soft furnishing (≥20 years old or from the USA), textile flooring (rug or carpet) ≥20 years of age) (b) urban /rural (c) numbers of electronic items were split at the median, and (d) split at 'vacuumed twice a week or more and dusted every week or more' for cleaning frequency.

Table SI13 Spearman's rho and correlation coefficients for PBDE concentrations in dust from different environments.

			Bedroom dust MB (ng/g) (n=24)			Living Room dust MB (ng/g) (n=24)			Workplace dust MB (ng/g) (n=8)		
			∑BDE47_99_100_153	BDE183	BDE209	∑BDE47_99_100_153	BDE183	BDE209	∑BDE47_99_100_153	BDE183	BDE209
Living Room dust MB (ng/g) (n=22)	∑BDE47_99_100_153	Correlation Coefficient	.427*	.127	-.009		.782**	.373	.899*	.841*	-.261
		Sig. (2-tailed)	.047	.572	.968		.000	.088	.015	.036	.618
		N	22	22	22		22	22	6	6	6
	BDE183	Correlation Coefficient	.355	.145	-.045	.782**		.127	.493	.551	-.551
		Sig. (2-tailed)	.105	.518	.841	.000		.573	.321	.257	.257
		N	22	22	22	22		22	6	6	6
	BDE209	Correlation Coefficient	.127	-.454*	.309	.373	.127		.103	.205	-.205
		Sig. (2-tailed)	.573	.034	.162	.088	.573		.870	.741	.741
		N	22	22	22	22	22		5	5	5
Home Office dust MB (ng/g) (n=4)	∑BDE47_99_100_153	Correlation Coefficient	1.000**	1.000**	.333	-1.000**	1.000**	-1.000**			
		Sig. (2-tailed)			.667						
		N	4	4	4	3	3	3	1	1	1
	BDE183	Correlation Coefficient	1.000**	1.000**	.333	-1.000**	1.000**	-1.000**			
		Sig. (2-tailed)			.667						
		N	4	4	4	3	3	3	1	1	1
	BDE209	Correlation Coefficient	.333	.333	1.000**	1.000**	-1.000**	1.000**			
		Sig. (2-tailed)	.667	.667							
		N	4	4	4	3	3	3	1	1	1
Workplace dust MB (ng/g) (n=8)	∑BDE47_99_100_153	Correlation Coefficient	.711*	.735*	.036	.899*	.841*	-.261		.595	.429
		Sig. (2-tailed)	.048	.038	.932	.015	.036	.618		.120	.289
		N	8	8	8	6	6	6		8	8
	BDE183	Correlation Coefficient	.398	.687	-.277	.493	.551	-.551	.595		.857**
		Sig. (2-tailed)	.329	.060	.506	.321	.257	.257	.120		.007
		N	8	8	8	6	6	6	8		8
	BDE209	Correlation Coefficient	-.055	.055	-.055	.103	.205	-.205	.143	.786*	
		Sig. (2-tailed)	.908	.908	.908	.870	.741	.741	.760	.036	
		N	7	7	7	5	5	5	7	7	
Vehicle dust MB (ng/g) (n=6)	∑BDE47_99_100_153	Correlation Coefficient	.896*	.896*	.358	.299	-.179	.179	.800	.400	.667
		Sig. (2-tailed)	.016	.016	.486	.565	.734	.734	.200	.600	.219
		N	6	6	6	6	6	6	4	4	5
	BDE183	Correlation Coefficient	.388	.388	-.508	-.090	.090	-.090	.200	.400	.410
		Sig. (2-tailed)	.447	.447	.304	.866	.866	.866	.800	.600	.493
		N	6	6	6	6	6	6	4	4	5
	BDE209	Correlation Coefficient	.806	.806	-.090	.090	-.090	.090	.400	.200	.564
		Sig. (2-tailed)	.053	.053	.866	.866	.866	.866	.600	.800	.322
		N	6	6	6	6	6	6	4	4	5

Notes: ** Correlation is significant at the 0.01 level (2-tailed), * Correlation is significant at the 0.05 level (2-tailed), not applicable

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