Dietary Exposure to Polychlorinated Biphenyls and Dioxins from Infancy until Adulthood: A Comparison between Breast-feeding, Toddler, and Long-term Exposure

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Food is the major source for polychlorinated biphenyl (PCB) and dioxin accumulation in the human body. Therefore, investigating food habits from early ages until reproductive age (25 years) is important in order to assess exposure risk for the next generation. The objective of this study was to assess the PCB/dioxin exposure and the relative contribution of different foods to total exposure during preschool age. Particularly, the importance of lactational PCB/dioxin exposure vs. dietary exposure until adulthood was investigated. A cohort of 207 children was studied from birth until preschool age. Based on 3 planar PCBs and 17 2,3,7,8-substituted dibenzo-*para*-dioxins (PCDDs) and dibenzofurans (PCDFs) measured in breast milk, a model was developed to calculate the cumulative toxic equivalent (TEQ) intake during breast-feeding (0–1 year). In 3.5-year-old children, daily dietary intake of planar PCB-TEQ and dioxin-TEQ was measured with a validated food questionnaire. Cumulative TEQ intake from 1 to 5 years was estimated using the PCB- and dioxin-TEQ intake measured with the food questionnaire. Cumulative TEQ intake from 6 to 25 years was estimated using national food consumption and contamination data of PCB- and dioxin-TEQ intake. In toddlers, dairy products contributed 43% to PCB-TEQ and 50% to dioxin-TEQ intake. Meat and meat products contributed 14% and 19%, respectively, and processed foods 23% and 15%, respectively. Breast-feeding for 6 months contributed to the cumulative PCB/dioxin TEQ intake until 25 years of age, 12% in boys and 14% in girls. The daily TEQ intake per kilogram body weight is 50 times higher in breast-fed infants and three times higher in toddlers than in adults. Long-term dietary exposure to PCBs and dioxins in men and women is partly due to breast-feeding (12 and 14%, respectively). After weaning, dairy products, processed foods, and meat are major contributors of PCB and dioxin accumulation until reproductive age. Instead of discouraging breast-feeding, maternal transfer of PCBs and dioxins to the next generation must be avoided by enforcement of strict regulations for PCB and dioxin discharge and by reducing consumption of animal products and processed foods in all ages. *Key words*: breast-feeding, cumulative intake, dietary exposure, dioxins, PCBs, preschool children, toxic equivalents. *Environ Health Perspect* 107:45–51 (1999). [Online 8 December 1998]
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Polychlorinated biphenyls (PCBs) and polychlorinated dibenzo-*para*-dioxins (PCDDs) and dibenzofurans (PCDFs) are halogenated aromatic compounds that are widespread and persistent environmental pollutants (*1*). The highly lipophilic and hydrophobic PCBs, dioxins (PCDDs and PCDFs), and related compounds tend to partition into soil and sediment, bioconcentrate from water to aquatic animal, and biomagnify up the multistep food chain (*1*). Humans are also high on the food chain, eating meat and dairy products from herbivores, as well as fish and plants (*1*). More than 90% of the total daily human exposure to PCBs and dioxins is made up of oral intake from food, whereas other routes, e.g., water, air and soil, contribute to less than 10% of total exposure (*2,3*). The average daily dose is about 1–3 pg/kg body weight (bw) of dioxinlike compounds considered equivalent in toxicity to 2,3,7,8-tetrachlorodibenzodioxin (TCDD) (*2*).

The human fetus is exposed to PCBs and dioxins through placental transport (*4–6*), and higher quantities of these compounds are transferred to the infant during breast-feeding (*7,8*). The concentration of these compounds in breast milk or cord blood is dependent on the maternal PCB and dioxin body burden. This body burden is the result of accumulation of PCBs and dioxins over many years, especially in fat tissue, combined with the low metabolic degradation and rate of excretion (*1*). As a result, the half-life is very long for higher chlorinated PCDDs and PCDFs, ranging between 4 and 12 years (*9*), and for PCBs, ranging between 5 and 15 years (*10*). Maternal age is positively related, and the period of previous breast-feeding is negatively related to maternal PCB and dioxin concentrations (*11*). Results from previous studies showed that the contribution of pregnancy-related diet to PCB and dioxin concentrations in human milk and in maternal and cord plasma was very low (*12*). The same was concluded when dietary intakes of PCBs and dioxins in preschool children were related to plasma PCB levels measured at preschool age (*8*). Short-term dietary regimens with low doses of dioxins during the lactation period showed no reduction in dioxin concentrations in breast milk (*13*).

Follow-up studies performed in children of women accidentally exposed to high levels of PCBs and related compounds (Japanese and Taiwanese rice oil incidents) have demonstrated a variety of health effects, e.g, lower birth weight, hyperpigmentation, conjunctivitis, nail changes, and developmental delay (*14,15*); these are similar to toxic effects reported in animal studies (*16*). Newborns of mothers who reported consumption of PCB-contaminated fish from Lake Michigan showed lower birth weight (*17*) and lower IQ scores at school-age (*18*). The PCB levels in the Michigan cohort were at or slightly above background levels.

As in other industrialized countries in Western Europe, contamination of breast milk with PCBs and dioxins in The Netherlands has led to considerable public concern. The Dutch government launched a longitudinal neurodevelopmental study in 1989 aimed at investigating the adverse effects of background exposure to PCBs and dioxins on growth and development of healthy full-term infants. The period of observation was expanded to preschool age in

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a European Community-funded European collaborative project. Previously reported results showed that in Dutch infants, lower birth weights and decreased postnatal growth (*19*), delays in psychomotor development (*20*) and neurodevelopment (*21*), alterations in thyroid hormone (*22*) and immunological status (*23*) were associated with prenatal PCB and dioxin exposure rather than with lactational exposure.

Given the results from the above mentioned studies and the bioaccumulation of PCBs and dioxins in the food chain, an estimate of dietary exposure to PCBs and dioxins from early ages until reproductive age is important in order to assess exposure risk for the next generation. In the present study, dietary intakes of PCBs and dioxins and the relative contribution of different foods to total PCB/dioxin exposure in Dutch preschool children are reported as assessed with a validated food questionnaire. We describe a model that represents the cumulative intake of PCBs and dioxins during breast-feeding versus the cumulative intake after breast-feeding, e.g., until 25 years of age.

Methods

Context of the study, subjects, and design. From 1990 to 1992, 207 mother–infant pairs were recruited in Rotterdam and the surrounding area, a highly industrialized area in The Netherlands. Infants included in the study were first or second children, born at full term, Caucasian, and without perinatal complications. To study the effects of prenatal and postnatal exposure to PCBs and dioxins, two groups of women were included: a group of women who intended to breast-feed their children for at least 6 weeks (the breast-fed group) and a group of women who intended to give formula (the formula-fed group) to their newborn infants. The formula (Almiron M2, Nutritia NV, The Netherlands) given to the infants had no detectable concentrations of PCBs and dioxins. Children were examined at 2 weeks; 3, 7, and 18 months; and 3.5 years of age for their growth and neurodevelopmental follow-up. At 3.5 years of age, 14 children (7%) were lost to follow-up: 10 were lost due to lack of interest and 4 due to inability to cooperate (illness in the family, separation, or emigration). Informed consent was given by participating parents, and the study protocol was approved by the medical ethics committee of the University Hospital Rotterdam, The Netherlands.

Four PCB congeners, 118, 138, 153, and 180, [International Union for Pure and Applied Chemistry (IUPAC) numbers] were measured in maternal plasma collected during the last month of pregnancy. These four PCB congeners were also measured in cord plasma collected directly after birth and in plasma samples collected from children at 3.5 years of age. All plasma samples were analyzed at the Nutrition and Food Research Institute, Zeist, The Netherlands, by gas chromatography with electron capture detection (GC-ECD). Methods of determination, laboratory validation, and quality control have already been published (*9,24*). Breast milk samples were analyzed for PCB and PCDD/PCDF congeners as described below.

TEQ intake of PCBs and dioxins during breast-feeding (0–1 year). In the second week after delivery, a 24-hr representative sample of breast milk was collected from breast-feeding mothers. Breast milk samples were analyzed for the 17 most abundant 2,3,7,8-substituted PCDD and PCDF congeners and 3 planar PCB congeners (PCBs 77, 126, and 169) by gas chromatography–high-resolution mass spectrometry (GC-HRMS) (*25*). Twenty-three nonplanar PCBs (IUPAC 28, 52, 66, 70, 99, 101, 105, 118, 128, 137, 138, 141, 151, 153, 156, 170, 177, 180, 183, 187, 194, 195, and 202) were measured by GC-ECD at the State Institute for Quality Control of Agricultural Products, Wageningen, The Netherlands (*25*). To express the total toxic potency of dioxins and planar PCBs, the toxic equivalent factor (TEF) approach was used according to Safe (*26*) and Ahlborg et al. (*27*). A TEF value was assigned to the dioxin and planar PCB congeners, which represents their relative toxic potency towards TCDD, the most toxic congener with a TEF value of 1. The toxic equivalents (TEQs) were calculated by multiplying the concentration (picograms per gram of milk fat) of each congener by its TEF value. Representative dioxin-TEQ and planar PCB-TEQ levels could be calculated for 83 and 95 milk samples, respectively. The remaining human milk samples were missing or not analyzed due to organizational failure. Levels and methods of determination of PCBs and dioxins in breast milk have been reported previously (*24,25*).

We used the planar PCB-TEQ and dioxin-TEQ values measured in breast milk to calculate the cumulative TEQ intake during breast-feeding in order to compare the TEQ intake during breast-feeding with the TEQ intake measured by the food questionnaire during preschool age and by national food consumption and contamination data. The cumulative TEQ intake during breast-feeding was calculated based on the following assumptions:

- An infant will drink an average of 800 ml/day from birth until 6 months of age (26 weeks) (*28–30*); 500 ml/day (*28*) from 6 to 9 months (27–39 weeks); and 400 ml/day from 9 months (>39 weeks) until cessation of breast-feeding. Breast-feeding period was reported by the mother as the number of weeks during which the infant was predominantly breast-fed.
- The literature indicates that 95% of all PCBs and dioxins are absorbed in the digestive tract (*31,32*).
- Several studies have shown that PCB and dioxin body burden of a mother during breast-feeding decreases by 20% every 3 months; therefore we used this percentage to calculate a weekly decrease of 1.7% in PCB and dioxin concentration in breast milk of each breast-feeding mother (*33,34*).

The following equation was used to calculate the cumulative planar PCB- and dioxin-TEQ intake (*I*) during the whole breast-feeding period:

$$I = 0.95 \times V \times [BMF] \times [TEQ]_{\text{breast milk}} \times \int_0^T e^{-0.017t}\, dt, \qquad (1)$$

where I = cumulative intake of planar PCB-TEQ and dioxin-TEQ from for each breast-fed infant during the period of breast-feeding (picograms), 0.95 = fraction of PCBs/dioxins absorption from breast-milk in the intestinal tract, T = period of breast-feeding in weeks, V = volume of breast milk consumed in milliliters per week, BMF = breast milk fat concentration in grams per milliliter, and TEQ = toxic equivalents of planar PCBs (IUPAC 77, 126, and 169) and 17 dioxin congeners measured in picograms per gram milk fat.

TEQ intake of PCBs and dioxins during the preschool period (1–5 years). At the age of 3.5 years, the primary caregiver of the child, usually the mother, was asked to fill out a semiquantitative food questionnaire (FQ) developed by the Division of Human Nutrition and Epidemiology, Agricultural University, Wageningen, The Netherlands. The FQ, which reflected the usual diet of the child over the last month, was validated against the dietary history method in a subgroup of the study population (n = 47) (*8*). The FQ was designed to assess dietary TEQ intake of 3 planar PCBs (IUPAC 77, 126, and 169) and 17 2,3,7,8-chlorine-substituted PCDDs and PCDFs, as well as energy, fat, carbohydrate, and protein intake in preschool children. The daily intake of PCB-TEQ and dioxin-TEQ was determined by calculating the TEQs of 3 planar PCBs and 17 2,3,7,8-chlorine-substituted dioxins in each food item (*26,27*) using reference data for food products provided by the National Institute of Public Health and the Environment (RIVM) (*3,35*). Intakes of energy, fat, protein, and carbohydrate were calculated

using the Dutch Food Database 1993 (*36*). Food intake data were converted into energy (kilojoules), nutrients (grams), and TEQs (picograms) using Komeet software (*37*). Daily total TEQ intake was defined as the sum of planar PCB-TEQ and dioxin-TEQ intake in picograms per day. From 193 children studied at 3.5 years of age, 183 FQs were available for analysis: 5 FQs were not returned or completed by the parents and 5 were excluded because of incomplete or unreliable answers.

The cumulative intake of dioxin-TEQ and planar PCB-TEQ from 1 to 5 years of age for boys and girls was calculated from the mean total TEQ and mean fat intake per day estimated from the FQ. The cumulative TEQ intake from 1 to 5 years of age was calculated for boys and girls separately according to the following equation, assuming an intestinal PCB/dioxin absorption of 95%:

$$I = 0.95 \times \text{Fat} \times [\text{TEQ}] \times 365.25 \times \text{Number of Years}, \quad (2)$$

where I = cumulative intake of planar PCB-TEQ and dioxin-TEQ (pg) from 1 to 5 years of age for boys and girls; 0.95 = fraction of PCBs/dioxins absorption in the intestinal tract; Fat = mean daily fat intake in grams for boys or girls, derived from the FQ; and TEQ = daily dietary intake of toxic equivalents of planar PCBs (IUPAC 77, 126, and 169) and 17 dioxin congeners measured in picograms per gram fat intake, derived from the FQ.

TEQ intake from childhood until adulthood (6–25 years). The cumulative TEQ intake from 6–25 years of age was calculated based on data from the RIVM (*35*) and the National Food Consumption Survey (FCS) (*38*). The FCS included comprehensive descriptions of intake of foods, energy, and nutrients of 6,218 persons in 1992 by age group and sex (*38*). Median intake of planar PCB-TEQ, estimated from RIVM data in the Dutch population, was 70 pg/day; this was 65 pg/day dioxin-TEQ, yielding a total TEQ intake of 135 pg/day (*39*). This value, in combination with a mean daily fat consumption of 92 g in the Dutch population derived from the FCS (*38*), yields a mean daily TEQ consumption of 1.47 pg/g fat. Using this value and values for mean daily fat consumption per age group and sex derived from the FCS 1992 (*38*), we calculated daily TEQ intake by sex and age group (6–10, 11–15, 16–20, and 21–25 years of age). The cumulative TEQ intake for men and women was calculated for each 5-year age group using the following equation, again assuming an intestinal absorption of 95%:

$$I = 0.95 \times \text{Fat} \times 1.47 \text{ pg TEQ/g fat} \times 365.25 \times \text{Number of Years}, \quad (3)$$

where I = cumulative intake of planar PCB-TEQ and dioxin-TEQ (picrograms) from 6–25 years of age for men and women, 0.95 = fraction of PCBs/dioxins absorption in the intestinal tract, and Fat = mean daily fat intake in grams, for men and women per age group, derived from the FCS (*38*).

Other variables. Information regarding socioeconomic background, obstetrical and neonatal history, maternal age, parents' education level, parity, and sex were obtained at birth. At 3.5 years of age, weight, height, and skinfold-thicknesses (mm) at four sites (bicipital, tricipital, subscapular, and suprailiacal) were measured according to Tanner and Whitehouse (*40*). Total body fat percentage was calculated from four skinfolds as described by Weststrate and Deurenberg (*41*).

Data analysis and statistical methods. The student t-test, chi-square test, and Mann-Whitney test, were used to compare differences between groups. The cumulative intake of PCB-TEQ and dioxin-TEQ during breast-feeding was calculated with the method of integration by pieces according to the volume of breast milk consumption varying over time (6–26 weeks, 27–39 weeks, >39 weeks). The predictive value of various variables for daily dietary TEQ exposure at 3.5 years of age was estimated by means of multiple linear regression analyses after adjustment for confounders. Results were considered statistically significant at $p \leq 0.05$. Data analysis was performed with SPSS for Windows (*42*).

Results

Table 1 shows general characteristics of the population. The original study population consisted of 207 mother–infant pairs. In infancy, 51% (n = 105) was breast-fed and 49% (n = 102) was formula-fed. The median of the breast-feeding period was 16 (range 6–72) weeks. The mean maternal age at

Table 1. Characteristics of the study group from birth to 3.5 years of age

Characteristic	Incidence
At birth (n = 207)	
Formula-fed	102 (49)[a]
Breast-fed	105 (51)[a]
Breast-feeding period (weeks)	16 (6–72)[b]
Sex	
Male	109 (53)[a]
Parity	
Firstborn	102 (49)[a]
Maternal age (year)	29 ± 4[c]
Maternal education[d]	
Low	40 (19)[a]
Middle	82 (40)[a]
High	85 (41)[a]
At 3.5 years (n = 193)	
Age (months)	42 (41–47)[b]
Weight (kg)	
Male	17.0 ± 2.1[c]
Female	16.4 ± 2.0[c]
Body fat[e] (%) (n = 163)	
Male	18.6 ± 3.2[c]
Female	20.9 ± 3.1[c]
Toxic compounds measured in plasma	
ΣPCB[f] maternal (µg/l) (n = 206)	2.04 (0.59–7.35)[b]
ΣPCB[f] cord (µg/l) (n = 182)	0.40 (0.08–2.08)[b]
ΣPCB[f] at 3.5 years (µg/l) (n = 173)	0.35 (0.08-5.90)[b]
Formula-fed group (n = 82)	0.21 (0.08–0.46)[b]
Breast-fed group (n = 91)	0.75 (0.23–5.90)[b]
Toxic compounds measured in breast milk (breast-fed group, n = 105)	
Fat percentage in breast milk (n = 105)	2.98 ± 0.71[c]
Planar PCB-TEQ[g] (pg/g milk fat) (n = 95)	14.8 (4.4–45.7)[b]
Dioxin-TEQ[g] (pg/g milk fat) (n = 83)	30.6 (11.1–76.4)[b]
Total TEQ[h] (pg/g milk fat) (n = 83)	46.9 (19.1–102.6)[b]

[a]Values shown are number (%).
[b]Values shown are median (range).
[c]Values shown are mean ± standard deviation.
[d]Low, primary school finished and secondary school not finished; medium, secondary school finished; high, high school finished/professional and university training.
[e]Body fat percentage was calculated from four skinfolds as described by Weststrate and Deurenberg (*41*).
[f]Sum of PCBs, IUPAC 118, 138, 153, and 180, measured in maternal, cord, and 3.5-year-old plasma samples.
[g]Toxic equivalents (TEQ) of planar PCBs (IUPAC 77, 126, and 169) and 17 substituted 2,3,7,8-PCDDs and PCDFs measured in breast milk samples.
[h]Total TEQ, the sum of PCB-TEQ and dioxin-TEQ in breast milk.

birth was 29 years, 19% of the mothers had a low level of education (primary school finished, secondary school not finished), 40% had a middle level education (secondary school finished), and 41% had a high level education (high school finished or professional/university training). The median sums of four PCB congeners measured in maternal plasma during pregnancy and in cord plasma were 2.04 and 0.40 µg/l, respectively. At 3.5 years of age, children in the breast-fed group had sum PCB levels that were nearly four times higher than sum PCB levels measured in the formula-fed group (0.75 vs. 0.21 µg/l; Table 1). Median planar PCB-TEQ, dioxin-TEQ, and total TEQ concentrations in breast milk were 14.8, 30.6, and 46.9 pg TEQ/g fat, respectively (Table 1).

Table 2. Daily intake of selected foods, energy, and macronutrients at 3.5 years of age according to sex

Nutrients	Male (n = 96)	Female (n = 87)
Foods		
Meat and fish		
Beef (g)	15 ± 12	12 ± 11
Pork (g)	12 ± 11	13 ± 10
Lean fish (g)	2 ± 6	2 ± 4
Fatty fish (g)	0.2 ± 1.0	0.3 ± 1.0
Dairy products		
Milk and milk products (g)	555 ± 251	533 ± 186
Cheese (g)	12 ± 11	15 ± 10
Butter (g)	2 ± 5	1 ± 4
Chicken and eggs		
Egg (g)	10 ± 8	10 ± 7
Chicken (g)	8 ± 8	8 ± 7
Vegetables and oils		
Vegetables (g)	42 ± 25	37 ± 22
Vegetable oil (g)	31 ± 7	30 ± 18
Nuts and seeds (g)	1 ± 2	1 ± 3
Industrial products		
Processed foods[a] (g)	115 ± 38	107 ± 34
Meat products (g)	31 ± 21	32 ± 19
Energy and macronutrients		
Carbohydrate (g)	208 ± 44	192 ± 35[b]
Protein (g)	59 ± 15	56 ± 12
Total fat (g)	69 ± 20	65 ± 18
Total energy (MJ)	7.1 ± 1.4	6.6 ± 1.3[b]

Values shown are means ± standard deviations.
[a]Processed foods except meat products.
[b]t-test, p<0.05.

The mean daily intake of selected foods, energy, and macronutrients at 3.5 years of age for males and females are presented in Table 2. Milk and milk products, industrial products, cheese, meat and meat products were consumed by nearly all preschoolers, whereas fish was consumed by a smaller group (29%) of children. Both energy and carbohydrate intake were significantly lower in females than in males (t-test, p<0.05; Table 2). Multiple linear regression analyses showed that energy, fat, carbohydrate, and protein intake at 3.5 years of age were significantly lower in the group with higher educated mothers (all p-values <0.01). Furthermore, body weight and body fat percentage at 3.5 years of age were positively associated with energy, fat, protein, and carbohydrate intake (all p-values <0.05).

At 3.5 years of age, the mean daily PCB-TEQ intake was 60 pg in the previously breast-fed group and 57 pg in the previously formula-fed group (not significantly different between groups). The mean daily dioxin-TEQ intake was 46 and 47 pg, respectively. No differences in mean daily PCB-TEQ and dioxin-TEQ was found between males and females (Table 3). The mean daily TEQ intake in males and females was 6.5 and 6.3 pg TEQ/kg bw/day. Four percent of children at 3.5 years of age exceeded the tolerable daily intake (TDI) of 10 pg TEQ/kg bw according to the World Health Organization (*43*), and 100% of all 3.5 year olds exceed the recommended TDI of 1 pg TEQ/kg bw/day by The Netherlands Health Council's Committee on Risk Evaluation of Substances/Dioxins 1996 (*44*). Multiple linear regression analyses showed that after adjustment for sex and body weight, daily intake of planar PCB-TEQ and dioxin-TEQ at 3.5 years of age were both significantly lower in children whose mothers had a high education level compared to children from mothers with a low and middle level of education (all p-values <0.01).

Figure 1 shows the contributions of different groups of food items to dietary intake of planar PCB-TEQ and dioxin-TEQ in preschool children. Dairy products, meat and meat products, and processed foods were the major contributors to dietary intake of PCB-TEQ and dioxin-TEQ. Dairy products contributed 43% to PCB-TEQ intake and 50% to dioxin-TEQ intake. Meat and meat products contributed 14% and 19% to PCB-TEQ and dioxin-TEQ intake, respectively, and processed contributed 23% and 15%, respectively. The contribution of fish was much lower (11% and 5%, respectively). Consumption of processed foods and fish contributed relatively more to PCB-TEQ intake than dioxin-TEQ intake.

In Figure 2, the cumulative intake of PCB-TEQ and dioxin-TEQ is plotted as a function of breast-feeding period in weeks. Three different curves are shown, based on the observed mean fat percentage in breast milk of 3% and total-TEQ concentrations

Table 3. Daily dietary intake of toxic compounds at 3.5 years of age by sex

	Male (n = 96)		Female (n = 87)	
	TEQ	TEQ/kg bw	TEQ	TEQ/kg bw
TCDD (pg)	8.0 ± 3.2	0.5 ± 0.2	7.5 ± 2.5	0.5 ± 0.2
Planar PCB-TEQ (pg)	61 ± 23	3.6 ± 1.5	57 ± 21	3.5 ± 1.4
Dioxin-TEQ (pg)	48 ± 6	2.9 ± 1.0	45 ± 14	2.8 ± 0.9
Total TEQ (pg)	110 ± 38	6.5 ± 2.4	102 ± 33	6.3 ± 2.3
Total TEQ/fat (pg/g fat)	1.60 ± 0.47		1.60 ± 0.43	

Abbreviations: TEQ, toxic equivalent; bw, body weight; planar PCB-TEQ, TEQs from planar PCB congeners, IUPAC 77, 126, and 169; dioxin-TEQ, TEQs from 17 substituted 2,3,7,8-polychlorinated dibenzo-p-dioxin and dibenzofuran (dioxin) congeners; total-TEQ, the sum of planar PCB-TEQ and dioxin-TEQ 1; total TEQ/g fat, total TEQ divided by grams of fat consumed (see Table 2). Values shown are mean ± standard deviation.

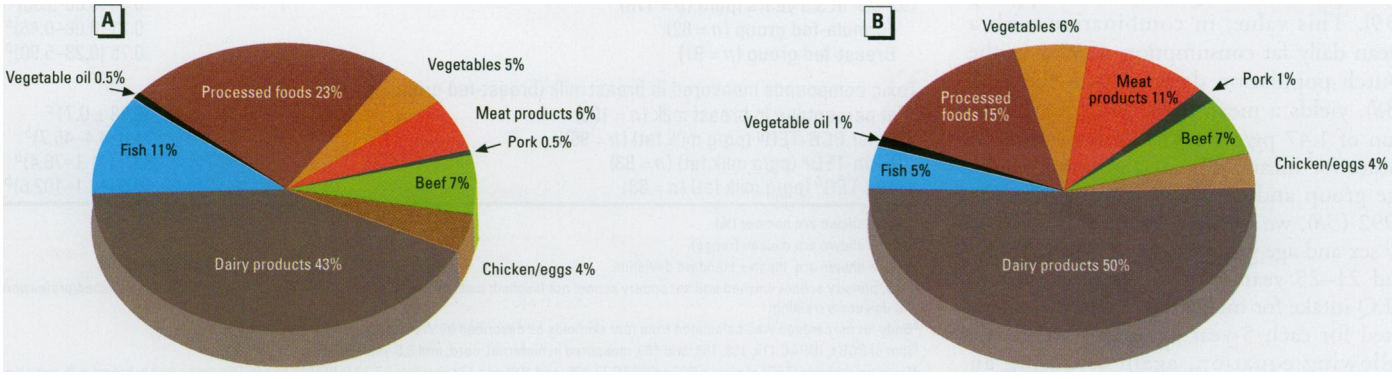

Figure 1. Contribution of different food groups (percentages) to dietary intake of planar PCB-TEQ (A) and dioxin-TEQ (B) in preschool children.

of 27.2 (10th percentile), 46.9 (50th percentile), and 69.6 pg TEQ/g fat (90th percentile) (see Fig. 2). Contaminant levels in breast milk and breast-feeding period are important determinants of the cumulative contaminant intake during breast feeding. For example, an infant breast-fed for 26 weeks with a relatively low TEQ concentration (10th percentile) in breast milk would have a similar cumulative intake as an infant breast-fed for 8 weeks by a mother with a relatively high TEQ concentration (90th percentile) in breast milk.

Table 4 represents the mean daily TEQ intake for males and females and the mean daily TEQ intake per kilogram body weight at different ages. Mean body weight standards of healthy Dutch children were used as reference data (*45*). The mean daily TEQ intake per kilogram body weight per day for infants receiving breast milk for 6 months was calculated according to the formula presented in Methods. For boys, this was 112 pg TEQ/kg bw, and for girls, this was 118 pg TEQ/kg bw, which is about 50 times higher than the mean daily TEQ per kilogram body weight from 20 to 25 years (2.3 and 2.0 pg TEQ/kg bw, respectively). The mean daily TEQ intake/kg bw during childhood (1–5 and 6–10 years of age) is two to three times higher than in adults (20–25 years of age).

Table 5 gives the estimated cumulative TEQ intake for infants who were either formula-fed or breast-fed for 3 and 6 months, respectively, both in micrograms and as a proportion of total dietary TEQ exposure until 25 years of age. The total cumulative TEQ intake over a 25-year period is 1.38 µg in men and 1.16 µg in women who were breast-fed for 6 months during infancy. Total cumulative TEQ intake in men and women at 25 years of age who were formula-fed in infancy is 1.22 µg and 1.01 µg, respectively. The TEQ intake during 6 months of breast-feeding accounts for 12% of the cumulative TEQ intake during 25 years in males and 14 % in females.

Discussion

In this study we assessed the dietary PCB and dioxin intake and the relative contribution of different foods to PCB and dioxin exposure in preschool children. The mean daily intake of planar PCB-TEQ and dioxin-TEQ in this population of Dutch preschool children is 59 and 47 pg, respectively. The mean daily intake of total TEQ for boys and girls is 6.5 and 6.3 pg/kg bw, respectively. The main contributors of PCB-TEQ and dioxin-TEQ in Dutch preschool children are dairy products, followed by processed foods, and meat and meat products. Fish plays only a marginal role with respect to PCB/dioxin exposure in this population.

Some limitations to the methodology of this study should be noted. The intake of PCB- and dioxin-TEQ at preschool age was estimated from a semiquantitative FQ combined with mean figures for TEQ content of foods in The Netherlands (*35*). Our numbers are somewhat higher for fat and energy intake (19% and 3%, respectively) when compared with the results from 3- and 4-year-olds in the FCS (*38*). We know of only one other study in children (n = 14; from 22 months to 5 years of age) in which dietary intake of dioxin-TEQ was measured by the duplicate method (*46*). Schrey et al. (*46*) measured a mean daily fat intake of 64 g (range 37–91 g) and a mean daily dioxin-TEQ intake of 44 pg (range

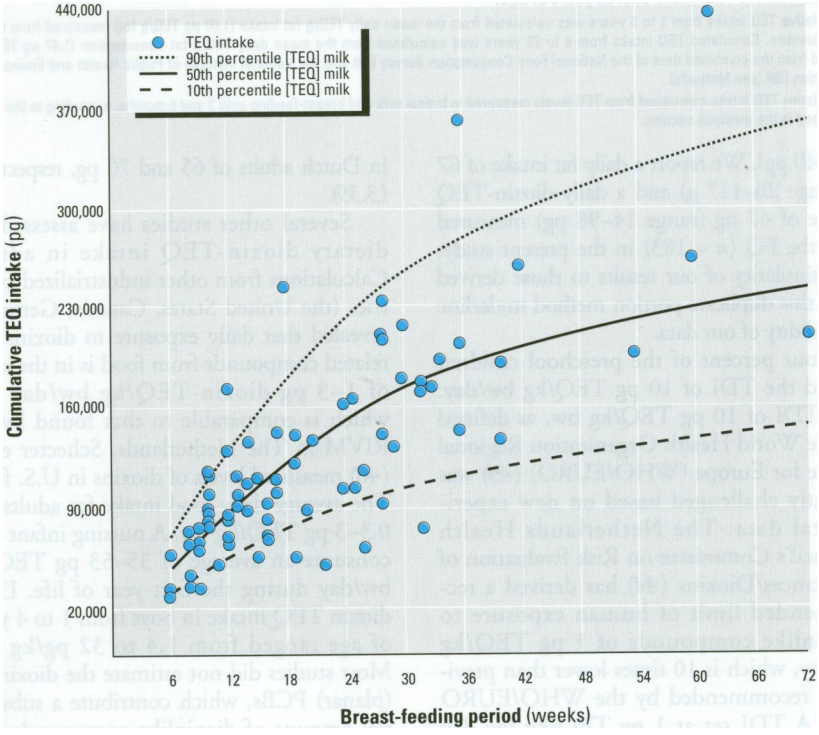

Figure 2. Cumulative intake of PCB and dioxin toxic equivalents (TEQs) as a function of breast-feeding period. Dotted lines are percentiles based on the observed mean fat percentage in breast milk of 3% and total-TEQ concentrations of 27.2 (10th percentile), 46.9 (50th percentile), and 69.6 pg TEQ/g fat (90th percentile) in breast milk.

Table 4. Estimated mean daily intake of PCB and dioxin toxic equivalents (TEQ) from birth until 25 years of age for males and females

	Males				Females			
Age group	Daily fat intake[a] (g)	Total daily TEQ intake (pg)	Mean bw[b] (kg)	Daily TEQ intake (pg/kg bw)	Daily fat intake[a] (g)	Total daily TEQ intake (pg)	Mean bw[b] (kg)	Daily TEQ intake (pg/kg bw)
Birth–6 months[c]	–	852	7.6	112	–	852	7.2	118
1–5 years[d]	69	110	17	6.5	65	102	16.4	6.3
6–10 years[e]	74	109	28.1	3.9	66	97	27.8	3.5
10–15 years[e]	98	144	47.4	3.0	88	129	48.2	2.7
16–20 years[e]	117	172	68.2	2.5	85	125	58.2	2.1
20–25 years[e]	116	171	70.8	2.4	86	126	58.6	2.2

Abbreviations: TEQ, toxic equivalents, sum of TEQs of 17 dioxin and 3 planar PCB congeners; bw, body weight; FQ, food questionnaire; FCS, national food consumption survey. Daily fat intake (g) multiplied by TEQ/g fat gives the total daily TEQ intake.

[a]Daily fat intake per age group and sex were derived from the FQ for the 1–5 year age group and from the FCS (*38*) for the 6–25 year age group.

[b]Mean body weight was derived from the weight standards of Dutch reference data for the 6–25 year age group (*45*) and from this study population for the 1–5 year age group.

[c]The estimated mean total-TEQ consumed per day was derived from cumulative intake during 6 months (26 weeks) of breast-feeding according to the formula described in Methods.

[d]Daily total-TEQ consumption was 1.60 pg TEQ/g fat, according to the FQ.

[e]The daily total-TEQ consumption of 1.47 pg TEQ/g fat was derived from the FCS (*38*) and the National Institute of Public Health and the Environment (*39*).

Table 5. Mean cumulative intake of dioxin-TEQ and planar PCB-TEQ presented from birth to 25 years of age according to sex; numbers are given for persons either formula-fed in infancy or breast-fed for 3 and 6 months in infancy

	Mean cumulative TEQ intake in µg (% of total)[a]					
	Male			Female		
		Breast-fed			Breast-fed	
Age group	Formula-fed	3 months	6 months	Formula-fed	3 months	6 months
0–3 months[b]	–	0.09 (7)	–	–	0.09 (8)	–
0–6 months[b]	–	–	0.16 (12)	–	–	0.16 (14)
0–5 years	0.19 (16)	0.27 (21)	0.35 (25)	0.18 (18)	0.27 (25)	0.34 (29)
0–10 years	0.38 (31)	0.47 (36)	0.53 (38)	0.35 (35)	0.43 (39)	0.50 (43)
0–15 years	0.63 (52)	0.71 (54)	0.78 (57)	0.57 (56)	0.66 (61)	0.73 (63)
0–20 years	0.93 (76)	1.01 (77)	1.08 (78)	0.79 (78)	0.88 (81)	0.95 (82)
0–25 years	1.22 (100)	1.31 (100)	1.38 (100)	1.01 (100)	1.09 (100)	1.16 (100)

TEQ, toxic equivalent for 17 dioxin congeners and 3 planar PCB congeners. Values in parentheses are percentages of the total cumulative TEQ intake until 25 years of age.

[a]Cumulative TEQ intake from 1 to 5 years was calculated from the mean daily TEQ/g fat intake (1.60 pg TEQ/g fat) measured from the food questionnaire. Cumulated TEQ intake from 6 to 25 years was calculated from the mean daily TEQ/g fat consumption (1.47 pg TEQ/g fat) derived from the combined data of the National Food Consumption Survey (*38*) and the National Institute of Public Health and Environmental Protection (*39*) (see Methods).

[b]Cumulative TEQ intake calculated from TEQ levels measured in breast milk and breast-feeding until 3 and 6 months, according to the formula described in the methods section.

19–140 pg). We report a daily fat intake of 67 g (range 26–117 g) and a daily dioxin-TEQ intake of 47 pg (range 14–98 pg) measured with the FQ (n = 183) in the present study. The similarity of our results to those derived from this duplicate portion method underline the validity of our data.

Four percent of the preschool children exceed the TDI of 10 pg TEQ/kg bw/day. The TDI of 10 pg TEQ/kg bw, as defined by the World Health Organization Regional Office for Europe (WHO/EURO) (*43*) was recently challenged based on new experimental data: The Netherlands Health Council's Committee on Risk Evaluation of Substances/Dioxins (*44*) has derived a recommended limit of human exposure to dioxinlike compounds of 1 pg TEQ/kg bw/day, which is 10 times lower than previously recommended by the WHO/EURO (*43*). A TDI set at 1 pg TEQ/kg bw day would be exceeded by 100% of 1- to 5-year-old children and almost all adults. The U.S. EPA uses a safe dose of 0.006 pg TEQ/kg bw/day, producing an upper-limit cancer risk of 10^{-6} (*47*). The amount of daily intake from birth until adulthood markedly exceeds these safety margins.

In 1991, the RIVM determined the dietary intake of planar PCB-TEQ and dioxin-TEQ in a representative sample of the Dutch population. Three planar PCBs and 17 2,3,7,8-chlorine-substituted dioxins and furans in different food samples were analyzed and combined with results from the National Food Consumption Survey (*3*). Using these combined data, a statistical model was developed to calculate the median daily TEQ intake in relation to age (*3*). The median daily intakes for adults were 1.4 pg PCB-TEQ/kg bw and 1 pg dioxin-TEQ/kg bw, resulting in median daily intakes of dioxin-TEQ and planar PCB-TEQ in Dutch adults of 65 and 70 pg, respectively (*3,39*).

Several other studies have assessed the dietary dioxin-TEQ intake in adults. Calculations from other industrialized countries (the United States, Canada, Germany) revealed that daily exposure to dioxins and related compounds from food is in the order of 1–3 pg dioxin-TEQ/kg bw/day (*2*), which is comparable to that found by the RIVM in The Netherlands. Schecter et al. (*48*) measured levels of dioxins in U.S. food. The average daily food intake for adults was 0.3–3 pg TEQ/kg bw. A nursing infant may consume an average of 35–53 pg TEQ/kg bw/day during the first year of life. Daily dioxin TEQ intake in boys from 1 to 4 years of age ranged from 1.4 to 32 pg/kg bw. Most studies did not estimate the dioxinlike (planar) PCBs, which contribute a substantial amount of dioxinlike compounds. We report a mean daily intake of 112–118 pg TEQ/kg bw in breast-fed infants and 6.3–6.5 pg TEQ/kg bw in 1- to 5-year-old children. Accounting for PCB-TEQ would at least double the total TEQ intake, which is in accordance with the U.S. EPA (*47*) and the study of Schecter et al. (*48*).

We estimated the cumulative PCB-TEQ and dioxin-TEQ intake from birth until 25 years of age. According to our model, breast-feeding for 6 months accounts for 12–14% of the dietary exposure until 25 years of age. The daily TEQ intake per kilogram body weight for infants breast-fed for 6 months is approximately 50 times higher than for adults, which was about the same as reported by the U.S. EPA (*47*). For children under 5 years of age, the daily intake per kilogram body weight is three times as high as in adults. The numbers presented should be regarded as an indication rather than as exact values because of the following limitations in the available data. Because we had no exact data on how much a breast-fed infant drinks per day, mean values from literature were used (*28–30*). Since the RIVM provides only mean values for PCB and dioxin concentrations from different foods, it was not possible to give a range or distribution of cumulative intakes (*35*). Furthermore, food preparation and/or cooking methods could have altered PCB and dioxin levels in the final product. Finally, it was not possible to account for additional PCB-TEQ intake of mono-*ortho* PCBs (IUPAC 105, 118, 156) because these PCB congeners were not included in the RIVM food analyses.

Although some model calculations of PCB and dioxin body burden and infant exposure through breast milk have been published (*34,49*), the cumulated PCB and dioxin intake from infancy until adulthood has not been previously quantitatively assessed. The cumulative intake as estimated in this study is not identical to body burden because losses by excretion and the long half-lives of different PCB and dioxin congeners are not taken into account. In the present paper, we report that the relative contribution of cumulative intake of PCB/dioxin TEQ in males and females until 25 years of age is 7% and 8%, respectively, when infants are breast-fed for 3 months and 12% and 14%, respectively, when infants are breast-fed for 6 months. These values are in the order of magnitude as model calculations by other authors (*34,49*).

Given that more than 10% of the cumulative TEQ intake until 25 years of age is due to 6 months of breast-feeding, limiting the nursing period might be considered. However, next to this disadvantage of PCB/dioxin accumulation in the infants' body during breast-feeding, there are numerous advantages of nursing itself on the general development of young children. Reports from our study (*20,50*) and others (*51*) showed that children who were breast-fed during infancy performed better on neurological and cognitive outcome measurements when compared with their formula-fed counterparts. Because the positive influences of nursing on child development outweigh the negative ones, we do not encourage shortening of the lactation period to achieve a lower PCB/dioxin body burden.

In conclusion, our results show that breast-feeding for 6 months makes up a reasonable proportion (12–14%) of the cumulative dietary PCB and dioxin exposure until reproductive age. The main food sources of PCBs and dioxins after weaning in young children are dairy products, processed foods, and meat and meat products. Given that

disturbances in growth and development in children are mainly related to *in utero* exposure rather than lactational exposure to PCBs and dioxins, we conclude that strict regulations and enforcement of these regulations could reduce the maternal PCB/dioxin body burden and thereby reduce the *in utero* and lactational exposure. Strategies should be directed toward reducing PCB and dioxin intake through the food chain at all ages and by lowering the consumption of animal products and processed foods, and not by discouraging breast-feeding.

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