A Longitudinal Examination of Factors Related to Changes in Serum Polychlorinated Biphenyl Levels

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Consumption of sport-caught fish from the Great Lakes is a recognized source of human exposure to polychlorinated biphenyls (PCBs). Understanding temporal changes in PCB body burden is crucial for evaluating exposure levels and augmenting validity of studies investigating their relationship to adverse health effects. Using data collected from 1980 to 1995, we evaluated longitudinal changes in serum PCB levels among 179 fisheaters and non-fisheaters of the Michigan Fisheater Cohort. Participants identified as fisheaters in 1980 ate 26 lb or more of sport-caught fish per year, whereas non-fisheaters ate less than 6 lb per year. We found a monotonic decline in serum PCB levels among all participants from a mean value of 24 ppb in 1980 to 12 ppb in 1994. This was paralleled by an 83% decrease in mean fish consumption among all participants over the same period. We combined demographic, lifestyle, and fish consumption information with PCB data and evaluated the data using regression models to identify predictors of PCB body burden over a 16-year period. Results of the mixed-effects linear regression model suggest that consumption of Lake Michigan fish before 1980, amount of sport-caught fish eaten in the past year, age, and year of data collection were significant determinants of current PCB body burden over the 16-year study period. PCB levels were particularly elevated for males who were classified as fisheaters in 1980, which may reflect higher levels of sport-caught fish consumption compared with female fisheaters. *Key words:* epidemiology, exposure assessment, fish consumption, Great Lakes, PCBs, serum. *Environ Health Perspect* 111:702–707 (2003). doi:10.1289/ehp.5866 available via *http://dx.doi.org/* [Online 21 January 2003]

Polychlorinated biphenyls (PCBs) have been linked to a broad range of adverse health effects in humans, from developing fetuses to aging adults (Fein et al. 1984; Hicks 1996; Lai et al. 2001; Persky et al. 2001; Rylander et al. 1998; Sauer et al. 1994; Schantz et al. 1996; Yu et al. 1991). However, efforts to ascertain historical PCB exposure and determine a causal relationship with health outcomes such as cancer and immune dysfunction have yielded inconsistent results (Hansen 1998; Kimbrough 1995; Wolff and Toniolo 1995). Information regarding changes in PCB body burden over time and the factors associated with these changes would greatly enhance our understanding of the role of PCBs in pathogenesis. However, longitudinal examinations of exposed populations are scarce and suffer from small sample sizes or insufficient time between measurements to examine the effects of longer-lived PCBs (Hovinga et al. 1992; Steele et al. 1986).

PCBs are a diverse group of organochlorines consisting of a biphenyl ring with 10 available positions for chlorination (Alford-Stevens 1986). In general, the half-life of PCBs in the body increases with increasing chlorination, and values have been estimated to range from < 1 year to 71 years (Phillips et al. 1989; Shirai and Kissel 1996; Yakushiji et al. 1984). However, the most common congeners to which the general population is exposed are characterized by half-lives of 2–6 years (Shirai and Kissel 1996). Thus, it may be difficult to determine complete historical exposure to PCBs, as biological measurements are often collected many years after exposures have occurred.

Ingestion of contaminated food products, especially contaminated sport-caught fish, is among the most important pathways of exposure to PCBs (Fiore et al. 1989; Humphrey 1976, 1983; Kreiss 1985). Factors related to fish consumption such as type of fish species consumed, number of years consuming sport-caught fish or wildlife, source of sport-caught fish, and fish preparation methods (removal of skin and fat) have been shown to influence serum PCB levels (Dellinger et al. 1996; Falk et al. 1999; Feeley 1995; Fiore et al. 1989; Fitzgerald et al. 1999; Hanrahan et al. 1999). Demographic factors are also strong predictors of PCB levels. Increasing age, male sex, and higher body mass index (BMI) have been associated with increased serum PCB concentrations (Falk et al. 1999; Feeley 1995; Hanrahan et al. 1999; Hovinga et al. 1993; Kearney et al. 1999; Kreiss 1985; Laden et al. 1999; Wolff et al. 1992). Occupational exposure in capacitor, transformer, and electrical equipment manufacturing industries is also associated with increases in serum PCB levels (Wolff 1985; Wolff et al. 1992). Reproductive factors, including parity and breast-feeding, appear to decrease body burdens of PCBs in reproductive-age women (Feeley 1995; Fitzgerald et al. 1998; Laden et al. 1999; Skaare and Polder 1990).

We undertook this investigation to evaluate changes in PCB body burden using a cohort of fisheaters and non-fisheaters that was established in 1980 by the Michigan Department of Public Health (MDPH) and followed periodically through 1995 (Hovinga et al. 1992; Humphrey 1983; Schantz et al. 1996). We sought to investigate the effect of changes in the consumption of sport-caught fish on levels of PCBs in the body and to identify other predictors of change in serum PCB levels over time.

Methods

Study population. From 1980 to 1982, the MDPH established a cohort of 572 fisheaters and 419 non-fisheaters [the Michigan Fisheater (MFE) Cohort] to evaluate the potential for human exposure to environmental contaminants through consumption of Lake Michigan sport-caught fish (Humphrey 1983). Detailed information regarding the MFE Cohort has been described previously (Hovinga et al. 1992, 1993; Humphrey 1983, 1992; Humphrey and Budd 1996; Humphrey et al. 2000). Briefly, fisheaters were selected based on the amount of sport-caught fish consumed [≥ 26 lb/year] and compared with randomly selected age-, sex-, and region-matched "non-fisheaters" who consumed < 6 lb of sport-caught fish per year. Self-reported demographic, medical history, and fish consumption information were obtained by personal interview. Unfortunately, questions about breast-feeding and parity were not included on the questionnaire.

A recharacterization of the MFE Cohort was undertaken by the MDPH from 1989 to

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1991 to obtain additional blood samples, update fish consumption histories, and obtain medical information (Humphrey and Budd 1996). Seventy-five percent of the cohort participated in this effort. In 1992, a subset of the cohort (104 fisheaters and 84 non-fisheaters randomly selected from those ≥ 50 years of age) was identified and participated in an investigation to evaluate neuropsychological functioning in which blood samples and questionnaire data were once again collected as part of the study protocol.

Although some changes to the original questionnaire were made in subsequent evaluations of the cohort, similar blood collection protocols were used in all three surveys. Blood samples were collected by phlebotomist field staff and analyzed by the MDPH, using the Webb-McCall packed-column gas chromatography analytic method to quantify total serum PCBs in all samples collected from the cohort (Hovinga et al. 1992, 1993; Humphrey 1983; Schantz et al. 1996); congener-specific analyses were carried out only on the samples collected during the last survey (Humphrey et al. 2000). The limit of detection for total PCBs in serum was 3 ppb throughout the study period.

In the current study, we included participants from the last investigation who had serum, demographic, and dietary information from at least two of the three characterizations of the cohort, yielding a sample size of 101 fisheaters and 78 non-fisheaters. Information was extracted from questionnaire data from 1980 to 1982 (hereafter referred to as 1980), 1989–1991 (1990), and 1993–1995 (1994) and compiled into a database. Self-reported height (feet) and weight (pounds) at each time point were used, after conversion of U.S. units to their metric equivalents, to estimate BMI [weight (kilograms)/height (square meter)]. Serum values below the limit of detection were assigned a value of 1.5 ppb, half the limit of detection (Hornung and Reed 1990). Seven subjects in 1980, three in 1990, and five in 1994 had serum PCB values below the limit of detection. PCB data were unavailable for 8 participants in 1980, 14 in 1990, and 10 in 1994.

Using information obtained on the number of sport-caught fish meals consumed per month and ounces of fish consumed per meal, the total pounds of sport-caught fish consumed in the past year were calculated. At enrollment in 1980, individuals were classified as non-fisheaters if they reported eating less than 6 lb of sport-caught fish in the past year. In the present study, non-fisheaters were assigned a value of 3 lb/year for 1980 consumption unless they reported no consumption of sport-caught fish in the past year, in which case they were assigned a value of 0 lb/year. Decreasing consumption of sport-caught fish among fisheaters and increasing consumption among non-fisheaters in later characterizations of this cohort made the designations of "fisheater" and "non-fisheater" assigned in 1980 misleading for some participants. Because our objective was to evaluate the relationship between serum PCB levels and consumption of contaminated Lake Michigan sport-caught fish over time, we evaluated these factors irrespective of 1980 designations of fish-eating status. We retained the 1980 fish-eating status designations in the current study only to reflect historical fish consumption patterns. Collection of data on primary fish species consumed and on cooking methods differed greatly among questionnaires. Therefore, these factors were not evaluated in the current study.

Statistical analysis. At each time point, normality of serum PCB values and total fish consumption in the past year was assessed using the Kolmogorov-Smirnov test. Serum contaminant values and total fish consumption were found to be log-normally distributed. Thus, the natural logarithm of PCB values were used in further statistical analyses. We evaluated differences in demographic factors by 1980 fisheater designation using a chi square test. Differences in the mean value of the log-transformed data for serum PCB levels or pounds of sport-caught fish consumed in the past year by demographic factors [age, sex, level of highest education received (less than high school, high school, or college), BMI (< 25 kg/m^2 or ≥ 25 kg/m^2), and region of residence (north, central, or south)] were examined using analysis of variance.

The relationship between log-transformed serum PCB levels and fish consumption (pounds of fish consumed in the past year) was first evaluated cross-sectionally using simple linear regression and then by multiple linear regression for each time point, 1980, 1990, and 1994. Demographic variables that were evaluated included age, sex, education, marital status, region of residence, and BMI. Although information was also collected on the total number of years consuming sport-caught fish, we were unable to evaluate its

Table 1. Demographic characteristics of study participants at enrollment in 1980 by fish-eating status[a] and for the data combined.

	Fisheaters (n = 101)		Non-fisheaters (n = 78)		All participants (n = 179)	
	No.	Percent[b]	No.	Percent[b]	No.	Percent[b]
Age group (years)						
< 50	45	44.6	40	51.3	85	47.5
50–59	42	41.6	24	30.8	66	36.9
60–69	13	12.9	14	17.9	27	15.1
70–79	1	1.0	0	0.0	1	0.6
Sex						
Male	47	46.5	29	37.2	76	42.5
Female	54	53.5	49	62.8	103	57.5
Education						
< High school	11	10.9	9	11.5	20	11.2
High school	45	44.6	24	30.8	69	38.5
> High school	45	44.6	45	57.7	90	50.3
Marital status						
Married	83	83.0	63	79.7	146	81.6
Single	2	2.0	1	1.3	3	1.7
Widowed	14	14.0	10	12.7	24	13.4
Divorced/separated	1	1.0	4	5.1	5	2.8
BMI (kg/m^2)						
< 25	43	42.6	43	55.1	86	48.0
≥ 25	58	57.4	35	44.9	93	52.0
Region of residence						
North	32	31.7	27	34.6	59	33.0
Central	28	27.7	32	41.0	60	33.5
South	41	40.6	19	24.4	60	33.5

[a]Participants identified as fisheaters in 1980 ate ≥ 26 lb sport-caught fish per year, whereas non-fisheaters ate < 6 lb/year. [b]Percentages may not add up to 100% because of rounding.

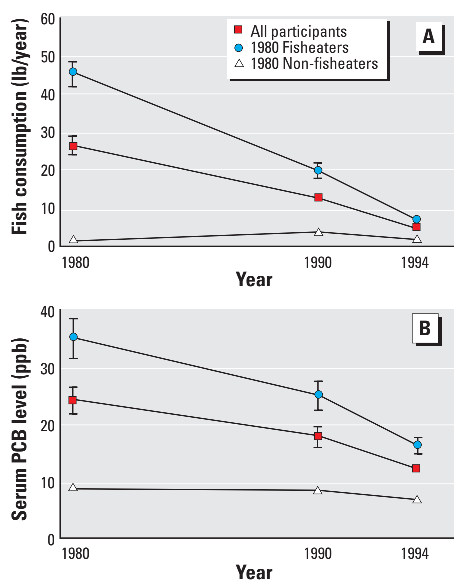

Figure 1. Mean fish consumption (*A*) and mean serum PCB level (*B*) by survey year for all participants and by 1980 fisheater designation.

contribution to serum PCB levels because of inconsistencies in the manner in which this variable was recorded over time. However, designation as a fisheater (consumption of ≥ 26 lb of sport-caught fish) or a non-fisheater (consumption of < 6 lb of sport-caught fish) at the time of enrollment in the study was also evaluated with regard to usual consumption over time, and this was determined to reflect an individual's typical sport-caught fish consumption. Thus, this designation was used to evaluate the influence of historical fish consumption on PCB levels.

Variables showing a statistical association ($p < 0.10$) with PCB serum concentration in the univariate models were evaluated in multiple linear regression models. Additionally, age, sex, and BMI, which were identified *a priori* through literature review to influence PCB levels, were retained in multivariate models regardless of statistical significance. A first-order interaction term between sex and 1980 designation of fish-eating status was identified during model building to significantly ($p < 0.05$) contribute to the prediction of PCB values and was thus included in the cross-sectional multivariate models. An interaction between sex and BMI was also examined but was not included in the final models, as it was not predictive of serum PCB levels.

To combine data across the three time periods and account for the possibility of the lack of independence between measurements collected on the same individual, mixed-effects models were applied to evaluate effects of important covariates on log-transformed serum PCB levels among study participants in 1980, 1990, and 1994. Variables that were evaluated included total sport-caught fish consumption in the past year, consumption of contaminated fish before 1980, age, sex, education, BMI, year of data collection, and an interaction term for sex and 1980 fish-eating status. We chose to model year of data collection categorically rather than continuously in the mixed-effects model, because changes in PCB levels did not appear proportionally distributed over time and would not have been accurately reflected by a linear time trend. All statistical analyses were performed using SAS software, version 8.01 (SAS Institute, Cary, NC).

Results

Demographic characteristics of study participants are presented in Table 1. In the total sample, there were nearly equal numbers who were < 50 years of age (48%) compared with older participants. Females (58%) were slightly more represented than males (43%). Nearly 89% of the study population completed at least a high school education, and 82% were married. In making comparisons by fisheater status, there were no significant differences by age, sex, education, or marital status. However, there was a slight difference in region of residence by fish-eating status ($p = 0.052$). Fisheaters also had a slightly higher mean BMI (26.0 kg/m^2) compared with non-fisheaters (24.9 kg/m^2), which was of borderline significance ($p = 0.059$).

Mean fish consumption (pounds) in the past year is presented by time period for all participants and by 1980 fisheater designations in Figure 1A. The annual consumption of sport-caught fish for all participants ranged from 0 to 185 lb in 1980, 0–99 lb in 1990, and 0–42 lb in 1994. There was a monotonic decline in mean consumption from 26 lb/year in 1980 to 13 lb/year in 1990 and 5 lb/year in 1994 for all participants.

Mean serum PCB values for all participants by time period are shown in Figure 1B. PCB values ranged from 1.5 to 203 ppb in 1980, 1.5–158 ppb in 1990, and 1.5–75 ppb in 1994. As with fish consumption, a decline in serum PCB levels was observed for all participants over time. Mean serum PCB concentrations for the total sample dropped from 24 ppb in 1980 to 12 ppb over the 16-year study period. Changes in serum PCB concentrations appear to be driven by diminishing fish consumption among those designated as fisheaters in 1980. Among fisheaters, mean serum PCB levels decreased 29% from 1980 to 1990 and 53% from 1980 to 1994. In contrast, participants designated as non-fisheaters in 1980 exhibited minimal changes in sport-caught fish consumption and moderate declines in serum PCB levels (9.1 ppb in 1980, 8.6 ppb in 1990, and 6.9 ppb in 1994). By 1994, sport-caught fish consumption, on average, was similar among fisheaters and non-fisheaters (6.7 and 2.0 lb/year, respectively).

Mean consumption of sport-caught fish (pounds) in the past 12 months stratified by demographic characteristics is presented in Table 2. Statistically significant differences in the mean values of the log-transformed data were observed with age and sex in 1990 and 1994 and with region of residence in 1980 and 1994 ($p < 0.05$). Mean serum PCB levels stratified by sociodemographic factors are presented in Table 3. Increasing age in 1994, male sex, and a BMI > 25 kg/m^2 at all time points were significantly related to higher log-transformed serum PCB levels.

Examination of the association between demographic and fish consumption variables and serum PCB levels by simple linear regression revealed statistically significant associations with increasing total sport-caught fish consumption, 1980 designation of fish-eating status, increasing age, and male sex for all time points ($p < 0.05$; data not shown). BMI was also found to be positively associated with serum PCBs in 1980 and 1990 by univariate analysis. Results of the 1980, 1990, and 1994 multiple linear regressions are presented in Table 4. In all models, a positive association between serum PCB levels and total pounds of sport-caught fish consumed in the past year was observed after controlling for other covariates ($p < 0.05$). Effects related to recent consumption of sport-caught fish appear to increase in each cross-sectional multivariate model over the 16-year interval. Fish-eating status, as per the 1980 designation, and age also contributed significantly to the prediction of serum PCB values among all participants at all three time points ($p < 0.05$). However, the effect of age appears relatively stable from 1980 to 1994, whereas the influence of fish-eating status as determined in 1980 appears diminished over time, which suggests that historical fish consumption exerts a persistent but decreasing effect on more recent biological PCB measurements.

Results from the mixed-effects model that evaluated the influence of sociodemographic factors and fish consumption on serum PCB

Table 2. Mean fish consumption (lb/year) by demographic characteristics and period of data collection.

	1980		1990		1994	
	No.	Mean ± 1 SE	No.	Mean ± 1 SE	No.	Mean ± 1 SE
Age group						
< 50	84	22.8 ± 2.9	37	8.7 ± 2.9	0	—
50–59	66	32.0 ± 4.5	41	15.4 ± 3.0	65	3.3 ± 0.6
60–69	27	23.1 ± 6.9	64	14.2 ± 2.2	60	7.4 ± 1.4
≥ 70	1	22.0	26	10.6 ± 3.4	53	3.1 ± 0.9
Sex						
Male	76	33.9 ± 4.2	72	17.1 ± 2.4	75	7.1 ± 1.2
Female	102	20.6 ± 2.7	96	9.4 ± 1.6	103	2.9 ± 0.5
Education						
< High school	20	39.0 ± 10.3	19	17.7 ± 5.6	19	9.8 ± 3.2
High school	69	31.2 ± 4.3	60	14.1 ± 2.1	63	5.3 ± 1.0
> High school	89	19.6 ± 2.4	89	10.7 ± 1.9	96	3.2 ± 0.6
BMI (kg/m^2)						
< 25	86	21.4 ± 3.0	88	10.9 ± 1.7	64	4.0 ± 0.9
≥ 25	92	30.8 ± 3.6	80	14.8 ± 2.2	114	5.0 ± 0.8
Region of residence						
North	59	22.5 ± 4.0	52	12.0 ± 2.1	59	3.3 ± 0.6
Central	60	23.5 ± 4.0	60	11.9 ± 2.5	59	4.9 ± 1.2
South	60	32.8 ± 4.4	56	14.3 ± 2.5	60	5.7 ± 1.2

levels over the 16-year time interval are shown in Table 5. Total pounds of sport-caught fish eaten in the past year, 1980 designation of fish-eating status, age, year of data collection, and the interaction term for sex and 1980 fish-eating status were found to be important determinants of log-transformed serum PCB levels ($p < 0.05$). Though not statistically significant, estimates for the main effect of sex and education suggest that males and individuals with a high school education or less have higher serum PCB levels. BMI did not contribute statistically to the prediction of serum contaminant concentration.

Discussion

Cross-sectional investigations have identified several factors associated with current PCB body burden among various exposed populations (Falk et al. 1999; Feeley 1995; Fiore et al. 1989; Fitzgerald et al. 1998; Hanrahan et al. 1999; Hovinga et al. 1993; Kreiss 1985; Laden et al. 1999; Skaare and Polder 1990; Wolff and Toniolo 1995). In contrast, information about factors that influence changes in PCB levels over time is lacking because of a paucity of studies that have conducted longitudinal exposure assessments, which limits our understanding of the role they might play in increasing the risk of adverse health outcomes. Thus, the current study provided a unique opportunity to examine long-term changes in serum PCB levels relative to historical and current levels of sport-caught fish consumption, as well as to sociodemographic factors, among 179 MFE Cohort participants from 1980 to 1995.

In this study, we observed a marked decrease in serum PCB levels among our study participants, which is paralleled by reduced consumption of sport-caught fish from Lake Michigan. Mean serum PCB levels for all study participants declined monotonically from 24 ppb in 1980 to 18 ppb in 1990, and to 12 ppb in 1994. The change in serum PCB levels from 1980 to 1990 reflects a 27% reduction in mean serum level, which was likely influenced by the 52% reduction in annual sport-caught fish consumption over the same period. Not surprisingly, the changes over the 16-year study period were even greater, with an 82% reduction in sport-caught fish consumption and a 49% decrease in mean serum PCB levels. Diminishing consumption over time may be a consequence of behavior modification due to aging, health concerns, dietary restrictions, or availability of sport-caught fish in Lake Michigan during that period. Although the posting of fishing advisories may have affected consumptions patterns for some participants, our data suggest that the majority of the study population did not modify their fish consumption as a result (data not presented).

Our findings of declining serum PCB levels are similar to changes in environmental PCB levels over time. Freshwater fish sampled from U.S. rivers and the Great Lakes by the National Biomonitoring Contaminant Program (NBCP) have provided evidence of declining environmental PCB levels in the United States (Schmitt et al. 1999). Approximately 94% of NBCP stations sampled in 1980 detected PCBs in the fish collected, with a geometric mean for total PCBs of 0.444 µg/g. By 1986, 20% fewer NBCP stations detected PCBs in fish sampled, and in those tissue samples with detectable levels, PCBs were present at lower concentrations (geometric mean of 0.335 µg/g) (Schmitt et al. 1999). Thus, it is likely that the degree of PCB contamination in the sport-caught fish consumed by our study participants lessened during the period between 1980 and 1995, which would have contributed to lowering PCB body burdens even had fish consumption patterns remained relatively stable over time.

Despite declines in serum PCB levels among this subset of the MFE Cohort, their PCB body burdens remain among the highest reported in the literature, with mean PCB levels of 12.4 ppb in 1994 among all participants and 6.7 ppb for those identified as non-fisheaters in 1980. The Agency for Toxic Substances and Disease Registry (ATSDR) reports that current background PCB levels among non-fisheaters in the general U.S.

Table 3. Mean serum PCB levels (ppb) by demographic characteristics and period of data collection.

	1980		1990		1994	
	No.	Mean ± 1 SE	No.	Mean ± 1 SE	No.	Mean ± 1 SE
Age group						
< 50	79	19.5 ± 2.8	36	13.5 ± 4.2	0	—
50–59	64	31.1 ± 4.6	41	17.1 ± 2.2	64	9.2 ± 1.1
60–69	27	22.5 ± 4.6	64	21.4 ± 2.7	58	14.2 ± 1.7
≥ 70	1	21.2	24	16.2 ± 3.3	47	14.6 ± 2.1
Sex						
Male	75	34.3 ± 4.6	71	23.7 ± 3.3	73	15.8 ± 1.8
Female	96	16.5 ± 1.6	94	13.4 ± 0.9	96	9.8 ± 0.7
Education						
< High school	20	24.3 ± 5.8	19	21.9 ± 5.2	17	13.1 ± 2.3
High school	67	25.8 ± 3.9	60	19.7 ± 2.7	60	14.4 ± 1.8
> High school	84	23.1 ± 3.3	86	15.7 ± 2.1	92	11.0 ± 1.1
BMI (kg/m^2)						
< 25	81	20.5 ± 3.5	87	13.4 ± 1.2	60	9.0 ± 0.7
≥ 25	90	27.7 ± 3.0	78	22.9 ± 2.9	109	14.2 ± 1.4
Region of residence						
North	59	24.5 ± 3.7	52	15.5 ± 1.9	54	13.8 ± 1.7
Central	55	24.5 ± 4.1	56	18.4 ± 3.2	58	12.0 ± 1.5
South	57	23.9 ± 4.2	57	19.6 ± 2.8	57	11.5 ± 1.7

Table 4. Results from the multiple linear regression models of log-transformed serum PCB levels (ppb) on sport-caught fish consumption and selected predictors at each survey period.

	1980		1990		1994	
Variable	$\hat{\beta}$	p-Value	$\hat{\beta}$	p-Value	$\hat{\beta}$	p-Value
Intercept	1.116	0.017	0.986	0.027	0.549	0.234
Sport-caught fish consumption (lb/year)	0.005	0.043	0.016	< 0.001	0.031	< 0.001
FE status[a]	0.821	< 0.001	0.476	< 0.001	0.390	0.002
Age (years)	0.020	0.001	0.011	0.048	0.020	< 0.001
Sex[b]	0.225	0.202	–0.167	0.260	–0.117	0.434
Education[c]	0.150	0.181	–0.065	0.509	–0.008	0.938
BMI (kg/m^2)	–0.012	0.468	0.016	0.208	–0.002	0.877
FE status[a] × sex[b]	0.428	0.059	0.487	0.014	0.474	0.014
n	171		159		168	
R^2	0.51		0.52		0.44	

Abbreviations: FE, 1980 fish-eating designation; *n*, number of observations.
[a]Referent category: non-fisheaters. [b]Referent category: female. [c]Referent category: ≤ high school education.

Table 5. Results from the mixed-effects model of log-transformed serum PCB levels (ppb) on sport-caught fish consumption selected predictors over 1980–1995.[a]

Predictor	$\hat{\beta}$	p-Value
Sport-caught fish consumption (lb/year)	0.005	< 0.001
FE status[b]	0.635	< 0.001
Age (years)	0.016	0.001
Sex[c]	0.061	0.661
Education[d]	–0.090	0.268
BMI (kg/m^2)	–0.015	0.072
1990 Survey[e]	–0.238	0.001
1994 Survey[e]	–0.596	< 0.001
Sex[c] × FE status[b]	0.510	0.005

FE, 1980 fish-eating designation.
[a]*n* = 179 individuals, 498 PCB measurements. [b]Referent category: non-fisheaters. [c]Referent category: female. [d]Referent category: ≤ high school education. [e]Referent category: 1980 survey.

population range from 0.9 to 2.2 ppb (ATSDR 2000). Given that our study population was enrolled during the period before and immediately after mass production of PCBs was halted in the United States and that participants who were identified as fisheaters in 1980 ate Lake Michigan sport-caught fish when the Great Lakes were contaminated with greater quantities of PCBs, the effect of heavy historical exposure is likely to continue to influence current body burden 16 years later.

Using cross-sectional multiple regression models, we identified age, amount of sport-caught fish consumed in the past year, and the 1980 designation of fish-eating status as important predictors of serum PCB concentration. Detailed examination of these cross-sectional models in chronological series reveals the consistent effect of increasing age and a declining influence of historical fish consumption on current serum levels with increasing importance of recent consumption. Designation as a fisheater in 1980 serves as an important proxy for past exposure to PCBs. This factor was consistently one of the most important predictors of serum PCB concentration, explaining approximately 27% of the total variation in PCB levels at all three periods of evaluation. In the earliest data-collection period for this cohort, substantial PCB exposures also resulted from consumption of other foods such as meat and dairy products, but PCB contamination of these food items has declined considerably over time (Laden et al. 1999). We speculate that the apparent increase in the effect of current sport-caught fish consumption on serum PCB levels may be a result of the declining influence from these other dietary sources.

Determinants of serum PCB levels in the cross-sectional statistical analysis of this study are consistent with factors identified previously by other investigators including age, sex, and amount of sport-caught fish eaten in the past year (Falk et al. 1999; Hanrahan et al. 1999; Hovinga et al. 1993; Kearney et al. 1999; Laden et al. 1999). Despite the lack of an association between BMI and serum PCB levels, the degree of adiposity is thought to modulate storage of PCBs (Birnbaum 1985; Feeley 1995). Nonetheless, evaluation of BMI as a predictor of current exposure in cross-sectional studies is sparse, and a consistency in findings has yet to emerge (Falk et al. 1999; Hovinga et al. 1993; Laden et al. 1999). Parity and breast-feeding play an important role in reduction of stored PCBs in breast tissue (Feeley 1995; Fitzgerald et al. 1998; Greizerstein et al. 1999; Skaare and Polder 1990). We did not have the data to evaluate the effects of parity and breast-feeding on the trends in contaminant levels observed in this study, but given that an eligibility criterion for this study was age ≥ 50 years in 1992, it is not likely that many of the women would have breast-fed their infants. The prevalence of breast-feeding in the United States during the period of relevance for these women (1960–1980) was very low. Breast-feeding declined steadily in this country from the 1950s (25% initiation) through 1975 (22% initiation) (Wright and Schandler 2001). When the rate of breast-feeding initiation began to rise in 1975, most of the cohort women would have completed their child-bearing years.

We applied a mixed-effects linear model to identify predictors of serum PCB levels over the 16-year study interval. Similar to the 1980, 1990, and 1994 cross-sectional multivariate models, fish consumption in the past year, heavy consumption of contaminated fish before 1980, increasing age, and an interaction between sex and historical fish consumption were the most important determinants of PCB concentration over the 16-year interval. Additionally, year of data collection contributed significantly to the model, with lower levels predicted at later time points. Clearly, these results demonstrate the influence of time and the elimination of persistent heavily chlorinated PCBs from the body on observed serum levels.

Although the literature has consistently reported that males have higher serum PCB levels compared with females (Falk et al. 1999; Feeley 1995; Hanrahan et al. 1999; Kreiss 1985; Wolff et al. 1992), our findings also suggest that differential consumption patterns in the past may modify the effect of sex. In evaluating average levels of sport-caught fish consumption by sex among fisheaters as reported in 1980, males (54 lb/year) consumed greater amounts of sport-caught fish than females (33 lb/year). As a result, differences in historical levels of sport-caught fish consumption may have resulted in increases in PCB stores in the body for males compared with females. Relative to female non-fisheaters and after adjustment for other covariates in the model (Table 5), the model predicts that serum PCB levels in 1980 are increased by factors of 5.5, 9.7, and 17.1 for male non-fisheaters, female fisheaters, and male fisheaters, respectively. When the interaction term between sex and fisheater status was not included in the analysis, more pronounced effects were noted for both fisheater status and sex (estimated regression coefficients of 0.842 ($p < 0.0001$) and 0.358 ($p = 0.0001$), respectively) with little or no changes in the estimated coefficients of the other variables in the model (data not shown).

A previous examination of the MFE Cohort included an initial assessment of a small pilot study sample assembled in 1973, the full cohort available in 1979–1982, and finally in 1989–1991 (He et al. 2001). Linking these three time intervals, after stratification by fisheater versus non-fisheater status, consumption of sport-caught fish, male sex, and increasing age were predictors of serum levels of Aroclor 1260. In the current study, the subset of the MFE Cohort examined again in 1993–1995 confirmed these predictors of serum PCB levels; however, whereas He et al. (2001) reported serum PCB levels stabilizing among the fisheaters at their final assessment, our results indicated that they continued to decline in this older subset of the cohort.

The findings of this study support evidence from the two longitudinal investigations of changes in serum PCB levels that report declining PCB exposure over time. Steele et al. (1986) noted gradually declining PCB levels among 11 electrical equipment manufacturing workers from 1977 to 1984. A similar pattern of longitudinal changes in PCB body burden is evidenced in a study that used data collected in 1982 and 1989 on 115 fisheaters and 95 non-fisheaters from the MFE Cohort (Hovinga et al. 1992). Mean serum PCB levels among fisheaters decreased 1.5 ppb ($p = 0.026$) over the 7-year interval, but did not differ statistically from the 0.2 ppb ($p = 0.79$) reduction observed among non-fisheaters. Although 57% of fisheaters decreased fish consumption during this period, multiple linear regression analyses did not reveal an association between changes in fish consumption and absolute or percent change in serum PCB levels (Hovinga et al. 1992) from 1982 to 1989. Limited duration of follow-up and use of a different subset of the MFE Cohort may be factors that explain the equivocal results when comparing the older study to the current investigation. Moreover, differences in the analytic approach may offer some explanation as well. Whereas the earlier study evaluated changes in serum PCB levels using a single measure, in which there may have been some loss of information in the summary statistic (Burton et al. 1998), we relied on linear mixed modeling that captures all of the information in the measurements that were available for analysis while accounting for the lack of independence among observations from the same individual.

This study is limited by availability of fish consumption data and use of self-reported information. We were constrained to information on total consumption of sport-caught fish in the year prior to data collection to evaluate the relationship with PCB body burden. Optimally, information on fish consumption patterns for all years before exposure assessment would be collected and used to evaluate longitudinal changes in serum PCB levels. Moreover, spikes in serum PCB measurements have been observed subsequent to consumption of contaminated fish (Kuwabara et al. 1979). Knowing the timing of biological sample collection with regard to consumption of last sport-caught fish meal would improve our ability to evaluate the relationship between fish consumption and serum PCB concentration. As with BMI, we were limited to self-reported recalled information obtained from participants. Ideally, more accurate measures of fish consumption and adiposity could be obtained in future studies through the use of daily food diaries and skin calipers to measure body fat, respectively.

In summary, this study demonstrates a monotonic decline in both consumption of sport-caught fish and serum PCB levels for all MFE participants from 1980 to 1994. Observed decreases in serum levels for study participants are mainly a result of diminishing Lake Michigan fish consumption among participants designated as fisheaters in 1980. The decreasing contribution of historical fish consumption and the increasing influence of recent sport-caught fish consumption on PCB body burden were also demonstrated. The most important determinants of serum contaminant levels over the 16-year study period were heavy fish consumption before 1980, total pounds of sport-caught fish eaten in the previous year, increasing age, year of data collection, and an interaction term for sex and 1980 fisheater designation, with male fisheaters having greater predicted serum PCB levels compared with male non-fisheaters, female fisheaters, and female non-fisheaters. Results of this study provide valuable information that can be used to develop PCB exposure assessments and better elucidate the relationship with adverse health effects in the future.

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