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Development of a Retrospective Job Exposure Matrix for PCB-exposed Workers in Capacitor Manufacturing

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Abstract: Development of a Retrospective Job Exposure Matrix for PCB-exposed Workers in Capacitor Manufacturing: Nancy B. Hopf, *et al*. Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Division of Surveillance, Hazard Evaluation and Field Studies, Industry-wide Studies Branch, USA—Objectives: Polychlorinated biphenyls (PCBs) are considered probable human carcinogens by the International Agency for Research on Cancer and one congener, PCB126, has been rated as a known human carcinogen. A period-specific job exposure matrix (JEM) was developed for former PCB-exposed capacitor manufacturing workers (n=12,605) (1938–1977). **Methods:** A detailed exposure assessment for this plant was based on a number of exposure determinants (proximity, degree of contact with PCBs, temperature, ventilation, process control, job mobility). The intensity and frequency of PCB exposures by job for both inhalation and dermal exposures, and additional chemical exposures were reviewed. The JEM was developed in nine steps: (1) all unique jobs (n=1,684) were assessed using (2) defined PCB exposure determinants; (3) the exposure determinants were used to develop exposure profiles; (4) similar exposure profiles were combined into categories having similar PCB exposures; (5) qualitative intensity (high-medium-low-baseline) and frequency (continuous-intermittent) ratings were developed, and (6) used to qualitatively rate inhalation and dermal exposure separately for each category; (7) quantitative intensity ratings based on available air concentrations were developed for inhalation and dermal exposures based on equal importance of both routes of exposure; (8) adjustments were made for overall exposure, and (9) for each category the product of intensity and frequency was calculated, and exposure in the earlier era was weighted. **Results:** A period-specific JEM modified for two eras of stable PCB exposure conditions. **Conclusions:** These exposure estimates, derived from a systematic and rigorous use of the exposure determinant data, lead to cumulative PCB exposure-response relationships in the epidemiological cancer mortality and incidence studies of this cohort.
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Key words: Cumulative exposure, Exposure assessment, JEM, Polychlorinated biphenyl

Epidemiologic studies involving human exposures to polychlorinated biphenyls (PCBs), a probable human carcinogen, consider the potential risk associated with levels of disease related to exposure to these chemicals in the workplace, and depend on a rigorous exposure assessment of the jobs performed. Our objective was to describe a general job exposure matrix (JEM) approach in a retrospective exposure assessment, for which typically few industrial hygiene data are available. JEMs generally provide better exposure estimates[1] than duration of employment, often used as a surrogate for exposure.

Former PCB-exposed capacitor manufacturing workers (n=12,605) employed at a plant in Massachusetts (1938–1977) constitute the largest U.S. cohort of former capacitor workers. Previous retrospective mortality studies at this plant did not find any relationship between duration of employment in jobs involving PCB exposure and the overall risk of cancer mortality[2, 3].

In a recent epidemiological study of this population (and another capacitor cohort), both liver cancer (trend *p*-value=0.071) and prostate cancer (trend *p*-value=0.0001) mortality increased with cumulative exposure, showing strong exposure-response relationships[4]. We describe here the development of the period-specific JEM leading to these results, which is being used in on-going studies of this cohort, and will be

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used in future studies.

Methods

Study population

During the four decades (1938–1977) PCBs were used as a dielectric fluid to fill capacitors at a plant in Massachusetts. The number of active employees steadily increased at the plant, peaking between 1955 and 1957 with more than 3,600 employees. From 1958 through 1969 the number employed fluctuated between 1,707 and 2,713 workers. The number of workers decreased from 1,264 in 1970 to 390 workers in 1976. Throughout the PCB era, women comprised 64–78% of the workforce, with a peak of 85% during World War II. During this period a total of 12,605 workers was employed. The cohort was mainly Caucasian (70%) and Cape Verdean (30%).

Production process and plant description

Both large and small capacitors were manufactured at the plant, and the capacitor manufacturing process and plant lay-out was as follows; Pre-Assembly was the first step in making a capacitor. Foil (or wire) and paper were wound together tightly around a core to form a bale. This operation was separated by a wall from other Pre-Assembly jobs due to performance requirements of having a clean bale. Connectors were welded manually to terminals on the capacitor tops. The assembled bale and capacitor top was then placed into the prefabricated capacitor can and welded shut. Large (i.e. room size) capacitors were assembled on the third floor and all other capacitors were assembled on the first floor in a large open area. The capacitor top had a small opening for filling with PCB oil, a process called impregnation, which was the second step in the capacitor making process. Before pumping in PCBs, large individual capacitors or trays of smaller capacitors were placed in a 200 gal (756 *l*) impregnation oven, heated to approximately 150°C and brought under a vacuum. Capacitors were held in the oven for 24–60 hr (125 hr maximum), depending on capacitor size, to remove all moisture. Small capacitors were impregnated on the first and second floors where 30 impregnation ovens operated simultaneously. Once impregnated, the capacitors were manually removed from the ovens and transported by pushcarts to the heat soak (i.e. the fill-hole soldering department) where the impregnation fill-hole was soldered shut by hand. Once the capacitors were sealed they were conveyed through a trichloroethylene (TCE) degreaser to remove excess PCB oil, and then painted. The heat soak and fill-hole soldering stations were located just in front of the degreasing station. Before packing and shipping, the capacitors were heat-tested in Post-Assembly to identify possible cracks. The Post-Assembly area was one large room not physically separated from the impregnation area. Rejected capacitors were repaired or salvaged. Other types of non-PCB-filled capacitors (mica, electrolytic, and tubular) were also manufactured before 1972, but to what extent is not known[5]. The plant continued operating after 1977, using other chemicals instead of PCBs.

PCB mixtures

Different PCB mixtures, commercially called Aroclors, were used over time. The difference among these PCB mixtures was the distribution of congeners, each with varying degrees of chlorination[6]. Aroclor 1254 (mean chlorination 54%) was used from 1939 until a switch was made to Aroclor 1242 (42% chlorination), and finally to Aroclor 1016 (41–42% chlorination) in 1976. The exact year of the change from Aroclor 1254 to Aroclor 1242 was not documented.

Industrial hygiene data

Three industrial hygiene surveys were performed at the plant between August 1976 and March 1977 by the US National Institute for Occupational Safety and Health (NIOSH) and by the company. A total of 113 PCB personal and area air concentration measurements (not congener specific) were taken with both impinger and Florisil solid sorbent tube methods (Table 1). Results did not differ by measurement method[7]. Area air samples (n=73) were collected in 14 plant areas of PCB use and non-use. Personal air samples (n=40) were collected for 11 of 732 different operations with emphasis on the most highly exposed jobs. Average personal PCB air levels ranged from 150 $\mu g/m^3$ (floorman, n=6) to 1,260 $\mu g/m^3$ (degreaser, n=1)[8]. The floorman, located in Pre-Assembly, moved parts to other plant areas as needed.

According to the industrial hygiene reports, efforts were made to reduce PCB fumes from the impregnation ovens by opening the doors to only one or two impregnation ovens at one time, rather than all 30 ovens. Ventilation included general ventilation and ceiling fans throughout the plant, and local exhaust ventilation for each impregnation oven. Filling the capacitors resulted in dripping wet carts of impregnated capacitors that had to be moved; however, very few workers wore protective gloves, aprons, or safety glasses[8]. Changes in plant physical lay-out were minor, although some departmental changes introduced around 1962, when several jobs within one department ceased to exist, could have resulted in exposure changes.

Development of the JEM

The JEM was developed in nine steps (Fig. 1). Step 1: All unique jobs between 1938 and 1977 were identified from work histories and process, physical, chemical, and plant information and available measurement data (Table 1) were evaluated. Step 2: Descriptions of job tasks and manufacturing processes in conjunction with plant layouts

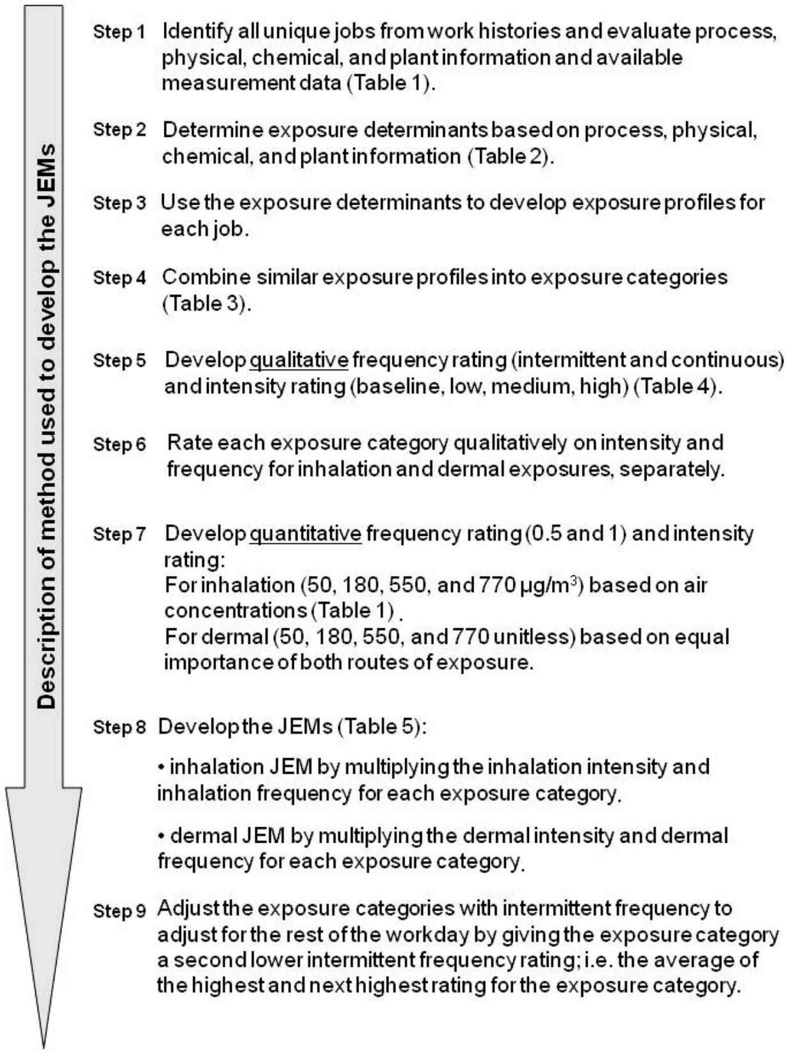

Fig. 1. Flow-chart of method used to develop the JEMs.

were used to develop a set of PCB exposure determinants and associated assessment criteria (Table 2). Step 3: A PCB exposure profile was developed for each job using these exposure determinants. This qualitative assessment of the job exposure profiles was performed by two NIOSH industrial hygienists having knowledge of the capacitor processing operations and materials used at the plant. Step 4: Jobs with similar exposure profiles were grouped to form a set of job exposure categories (cat). Jobs without any descriptions in the work histories were grouped into an "exposure unknown" category (cat. 26) (Table 3). Step 5: Qualitative evaluation criteria were developed for assigning inhalation and dermal exposure intensity ratings (Table 4). Step 6: Each job exposure category was assigned an intensity (high, medium, low, or baseline) and frequency (continuous or intermittent) rating separately for inhalation and dermal exposures; baseline rating was reserved for office workers. Exposure categories equally rated for PCB intensity and frequency were not collapsed into a single category if they involved different additional chemical exposures (TCE, exhaust, machine grease, oils, solvents, metal fumes, metal oxides, acids, solder fumes, combustion products of PCB, and welding fumes). Step 7: Numerical values were assigned to the qualitative rankings (high, medium, low, and baseline intensity; continuous and intermittent frequency). To determine the average inhalation value associated with each intensity rating, all available personal and area air concentration data for job exposure categories assigned to the rating were averaged. Frequency ratings of "continuous" and "intermittent" were given values of 1 and 0.5, respectively. Step 8: The intensity value was multiplied by the frequency value to determine the inhalation exposure level ($\mu g/m^3$) for each exposure category. Step 9: In the case of intermittent frequency, the exposure level was the sum of half the highest

Table 1. Measurement data: Summary statistics for personal and area PCB air concentrations (n=113) by exposure intensity rating

Intensity rating	Area air concentrations (μg/m^3) N=73	Personal air concentrations (μg/m^3) N=40	All concentrations (μg/m^3) N=113
High			
n	27	29	56
Mean	760	760	770
GM	690	710	700
GSD	2,300	1,900	1,500
Range	270–1,780	330–1,260	270–1,780
Medium			
n	24	4	28
Mean	600	290	550
GM	520	290	470
GSD	3,000	1,100	1,700
Range	210–2,670	250–320	210–2,670
Low			
n	20	7	27
Mean	200	190	180
GM	120	180	130
GSD	2,100	1,100	2,100
Range	30–1,560	140–260	30–1,560
Baseline (reference)			
n	2	0	2
Mean	50	NA	50
GM	50	NA	50
GSD	1,000	NA	1,000
Range	50	NA	50

GM=geometric mean, GSD=geometric standard deviat.

Table 2. Exposure determinants used to assess job exposure profiles

Exposure determinant	Assessment criteria (example) [outcome]
Proximity to PCB sources	· Distance to a liquid PCB source(s) (impregnation ovens, tanks, salvage and repair station) [at/ near/ far] · Distance to adjacent PCB jobs [at/ near/ far] · Physical separation (e.g. walls, enclosures) between departments [yes/no]
Direct or indirect contact with PCBs	· Job tasks involve direct contact with PCB liquid, aerosol, or vapor [yes/no] · Job tasks involve contact with PCB-contaminated surfaces/equipment [yes/no]
Temperature	· Elevated temperature (impregnation and leak testing) [yes/no] · Not elevated temperature [yes/no]
Ventilation	· Local exhaust ventilation (soldering, welding, and tank room jobs) [yes/no] · Dilution ventilation (oven area) [yes/no]
Process control	· Open / Closed · Automated/ Semi-automated/ Manual · Process frequency [low/high]
Job mobility	· Job tasks located in one area [yes/no] · Job tasks located in different areas in the plant (e.g. maintenance workers) [yes/no]

Table 3. Exposure categories: Description of 29 PCB job exposure categories by PCB manufacturing and non-manufacturing processes

No.	Job exposure category	Task description
Manufacturing		
	Pre-assembly	
29	Winding operator	Operated winding and foil machines
18	Pre-assembly worker	Combined capacitor parts to form pre-fabricates
27	Welder	Welded capacitor parts to make capacitor cans
5	Electrical worker	Assembled and tested electrical equipment in capacitor pre-assembly area
4	Dry inspector/Operator	Inspected or operated non-PCB machines
10	Machinist	Operated and maintained machines, set up new machines
	Impregnation	
9	Large-capacitor worker	Assembled and filled large capacitors
12	Process control worker	Controlled impregnation cycles of ovens and tanks
25	Kettle & Oven operator	Operated the heat reaction kettles/tanks with liquid PCBs
28	Wet inspector/Operator	Inspected or operated machines using PCBs
24	Solderer	Soldered impregnated capacitors shut
2	Degreaser	Operated TCE degreaser to remove PCBs on capacitor surfaces after impregnation
16	Painter/Sealer	Sealed and/or painted finished capacitors
11	Maintenance worker	Maintained equipment
13	Material handler/Floorman	Moved materials between workstations
3	Driver	Filled storage tanks with PCB from tank cars
	Post-assembly	
17	Post-assembly worker	Assembled small capacitors after impregnation
14	Metal coating operator	Sprayed capacitors with metal coating
19	Repair/Salvage worker	Repaired and salvaged rejected capacitors
1	Checker/Receiver/Packer	Handled finished capacitors in plant areas remote from PCB-processing jobs
8	Stock material worker	Moved materials from shipping to storage rooms
23	Shipping worker	Handled shipping paperwork
Non-manufacturing		
6	Engineer	Designed and developed processes and equipment
7	Fireman	Fire and emergency response
15	Office worker	Did paper work
20	Research lab worker	Worked in the laboratory
21	Salaried worker	Managers and higher educated workers (e.g. advertising, statisticians)
22	Security worker	Patrolled the plant
26	Unknown	Jobs missing titles and descriptions

anticipated intensity value and half the next lowest intensity value. (e.g. [0.5 × high intensity value] + [0.5 × medium intensity value]). Exposure categories assigned an "intermittent" frequency were expected to have higher exposure variability than those assigned a "continuous" frequency, hence the partial weighting of the intensity values.

The same process was used to assign the dermal exposure level for each JEM exposure category. Since dermal measurements were not performed and there was no way to determine the comparative importance of the dermal and inhalation routes of exposure, the scale for dermal intensity exposure was arbitrarily set the same as for inhalation intensity exposure, i.e., the same values for high, medium, low and baseline exposures were used.

We assumed greater opportunity for PCB exposures in the period prior to the 1960s because the saturation of plant surfaces with PCB was probably achieved early and the general awareness of industrial hygiene practices increased starting in the late 1950s and early 1960s. At this time, industries substituted Aroclor 1254 with Aroclor 1242, a less "toxic" dielectric fluid. We chose 1958, to represent the division between the two eras of exposure: the first era with Aroclor 1254 and higher exposure due to lack of industrial hygiene awareness, and the later era, reflecting better work practices using Aroclor 1242. By

Table 4. Qualitative ratings: Evaluation criteria for high, medium, low, and baseline inhalation and dermal exposure intensity ratings

	Evaluation criteria	
Intensity rating	Inhalation	Dermal
High	Jobs located in areas with PCB sources High temperature processes PCB in air and air levels higher than "Medium" rating Spills common	Jobs involved direct contact with PCBs AND PCB-contaminated surfaces Surfaces were covered with PCBs Spills common
Medium	Jobs performed adjacent to the PCB sources or mobile jobs in/out of PCB source areas PCB in air and air levels higher than "Low" rating Spills occasional	Jobs involved handling objects with PCB contaminated surfaces Surfaces were covered with PCBs Spills occasional
Low	Jobs performed in areas distant to the PCB sources PCB in air and air levels higher than "Baseline" rating	Jobs involved handling PCBs only during spills from accidents
Baseline (Reference)	Location remote from the capacitor production	Rare contact with PCBs

expert judgment, a modification factor of 1.2 or 20% more exposure for the early time period seemed reasonable since no lay-out, ventilation, or equipment changes occurred at this plant. The combined JEM was modified by multiplying jobs performed prior to 1958 with the era specific modification factor of 1.2.

Results

A total of 1,684 unique jobs was identified from company records across all departments and operations (step 1). Each unique job was assigned a job exposure profile based on exposure determinants (Table 2) (step 2). After combining similar job exposure profiles (step 3), 29 job exposure categories were created (step 4) (Table 3). Step 4 resulted in six manufacturing job exposure categories in Pre-Assembly (cat 4, 5, 10, 18, 27, 29), ten in Impregnation (cat 2, 3, 9, 11–13, 16, 24, 25, 28), six in Post-Assembly (cat 1, 8, 14, 17, 19, 23), and seven in non-manufacturing job (cat 6, 7, 15, 20–22, 26).

Pre-assembly: Foil machine operators were included with winding machine operators (cat 29) because the winding and foil departments were in close proximity and separated from other Pre-assembly jobs by a wall. Other Pre-assembly jobs were performed in a large area with no physical boundaries among the work stations. Jobs with comparable exposure patterns according to the previously described exposure determinants were categorized together: dry inspector/operator (cat 4), electrical worker (cat 5), machinist (cat 10), maintenance worker (cat 11), material handler/ floorman (cat 13), welders (cat 27), and all other pre-assembly jobs (cat 18). These jobs were at a stage in the process before PCBs were added to the capacitors; exposure levels were low or baseline.

Impregnation: Large capacitors were manufactured on a separate floor from the impregnation ovens and were filled with other oils in addition to PCBs. This reduced the potential PCB exposure among these workers as compared to PCB-only capacitor workers, thus warranting a separate category for large-capacitor workers (cat 9). Jobs involving impregnation of all other capacitors were categorized together (oven and kettle operators-cat 25). Workers in jobs in this category (cat 25) had more direct contact with PCBs than did the process workers controlling the impregnation (cat 12). Although heat soak and fill-hole soldering (cat 24), painting/sealing (cat16), and degreasing (cat 2) were performed in adjacent open areas, the tasks were judged to result in different degrees of PCB inhalation and dermal contact; thus, these jobs were placed in three exposure categories. Solderers (cat 24) were handling capacitors dripping wet with PCBs, and were located in the vicinity of the degreaser, exposing them to PCB vapors and soldering fumes. These fumes could potentially contain breakdown products of PCBs known to be more potent than the mother compounds[9]. The degreasing machine was contaminated with PCBs, and leaked at times. Exposure to aerosolized PCB and TCE was the rationale for categorizing degreasing jobs

Table 5. Job exposure matrices: Assigned frequency and intensity (primary and secondary) for the inhalation and dermal JEMs, including calculated exposure levels (concentrations) for each JEM

		Inhalation JEM ($\mu g/m^3$)				Dermal JEM				
	Exposure category	Frequency[A]	Intensity[B] 1°	Intensity[B] 2°	Exposure level	Frequency	Intensity 1°	Intensity 2°	Exposure level	Other exposures
01	Checker/Receiver/Packer	C	L		180	C	L		180	
02	Degreaser	I	H	M	660	I	H	M	660	TCE[C]
03	Driver	C	L		180	I	M	L	365	Exhaust
04	Dry inspector/Operator	C	L		180	C	L		180	Machine grease
05	Electrical worker	C	L		180	C	L		180	
06	Engineer	C	L		180	I	M	L	365	
07	Fireman	C	B		50	C	B		50	
08	Stock material worker	C	L		180	C	L		180	
09	Large-capacitor worker	I	M	L	365	I	H	M	660	
10	Machinist	C	L		180	I	M	L	365	Machine grease
11	Maintenance worker	I	M	L	365	I	H	M	660	Oils, grease, solvents, soap and water
12	Process control worker	C	H		770	C	H		770	
13	Material handler/Floorman/Racker	I	M	L	365	I	M	L	365	
14	Metal coating operator	C	L		180	C	L		180	Metal fumes, metal oxides, acids
15	Office worker	C	B		50	C	B		50	
16	Painper/Sealant worker	C	L		180	C	L		180	Organic solvents in paint
17	Post-assembly worker	I	H	M	660	C	H		770	
18	Pre-assembly worker	C	L		180	C	L		180	
19	Repair/Salvage worker	I	H	M	660	C	H		770	
20	Research worker	I	M	L	365	I	M	L	365	
21	Salary	C	B		50	C	B		50	
22	Security worker	C	B		50	C	B		50	
23	Shipping worker	C	L		180	C	L		180	
24	Solderer	I	H	M	660	C	H		770	Solder fumes, and combustion products of PCB
25	Oven & Kettle operator	C	H		770	C	H		770	
26	Unknown									
27	Welder	C	L		180	C	L		180	Welding fumes
28	Wet inspector/Operator	I	M	L	365	I	H	M	660	
29	Winding operator	C	L		180	C	L		180	

[A] Frequency of exposure (I = intermittent, C = continuous), given values of 0.5 and 1, respectively; [B] Intensity of exposure (H=high, M=medium, L=low, B=baseline); The intensity rating assigned in the JEM process Step 6 is denoted 1°, and the second intensity rating for exposure categories with intermittent frequency (Step 9) is denoted 2°. The values assigned for intensity (baseline to high) are 50, 180, 550, and 770, respectively, before modification by frequency of exposure. [C] TCE=trichloroethylene.

separately (cat 2). Maintenance jobs (cat 11), material handlers (cat 13), inspectors of machines using PCBs (cat 28), and drivers who filled storage tanks with PCBs from tank cars (cat 3) were given their own separate category because of their particular exposure profiles.

Post-assembly. The most remarkable PCB exposure pattern in Post-Assembly was the salvage and repair jobs (cat 19), where PCB exposures would fluctuate with the number of faulty capacitors. Salvage and repair jobs involved reaching into the PCB oil. No other jobs were similar to these jobs, warranting a separate category (cat 19). In Post-assembly, capacitors were sprayed with a metal coating, therefore these jobs (cat 14) had additional exposures (solvents and metals) compared with the general Post-assembly jobs (cat 17) and were given a separate category. Exposure profiles in the other three Post-assembly jobs (cat 1, 8, 23) were grouped together according to the exposure profiles as described in methods.

The numbers of job exposure categories assigned inhalation intensity ratings of “low” were 13 (45%), “medium” 5 (17%), “high” 6 (21%), “baseline” 4 (14%), and “unknown” 1 (3%). A dermal intensity rating of “low” was assigned to 10 (34%) exposure categories, “medium” to five (17%), “high” to nine (31%), “baseline” to four (14%), and “unknown” to one (13%). Inhalation and dermal exposure each had 19 (66%) of the exposure categories assigned a frequency rating of “continuous”, 9 (31%) “intermittent”, and 1 (3%) “unknown”, although the exposure categories assigned to each rating were not always the same.

The majority of the categories were rated continuous (n=16) or intermittent (n=6) for both inhalation and dermal exposure frequency. Three categories (cat 17, 19 and 24) were rated intermittent for inhalation frequency and continuous for dermal frequency exposure. Three categories (cat 3, 6 and 10) were rated continuous for inhalation frequency and intermittent for dermal exposure frequency.

Some categories were rated differently for inhalation and dermal exposure. Three categories were rated “medium” for inhalation intensity exposure and “high” for dermal intensity exposure: large capacitor workers (cat 9), maintenance worker (cat 11), and wet inspectors/operators (cat 28). Three categories were rated “low” for inhalation intensity exposure and “medium” for dermal intensity exposure: drivers (cat 3), engineers (cat 6), and machinists (cat 10).

As a consequence of the different objectives of the industrial hygiene surveys performed at the plant, air concentrations were available only for 20 of the 29 job exposure categories. Table 1 lists the descriptive statistics (range, mean, geometric mean, geometric standard deviation, n) using all air concentrations (and also using only personal or only area air concentrations) for groups rated high, medium, low, and baseline for PCB exposures.

Salaried workers (cat 21) would have been used as baseline, but unfortunately neither job descriptions nor air concentrations existed for this category. Therefore office workers (cat 15), were used for the baseline intensity rating, and this category was represented by two air concentrations (both 50 $\mu g/m^3$), which was set as the baseline value. All air concentrations (n=56) representing the high inhalation intensity exposure categories (cat 2, 12, 24, 25, and 28) were combined and the mean was calculated as 770 $\mu g/m^3$. Of the five medium inhalation intensity exposure categories (cat 9, 11, 13, 20, and 28) only one category (28) had air concentration data (n=28). The mean for the medium inhalation intensity exposure was calculated as 550 $\mu g/m^3$. Twenty-seven air measurements representing four (cat 4, 18, 23, 29) of thirteen low inhalation intensity exposure categories, yielded a low inhalation intensity exposure mean of 180 $\mu g/m^3$.

There were 18 intermittent PCB exposure ratings where the overall intensity was modified by adding the average of the highest and the next highest rating for the exposure category (step 9). For example PCB exposures for degreasers (cat 2) were rated high (770 $\mu g/m^3$) intensity and intermittent (0.5) frequency for inhalation, giving a second adjustment rating of medium (550 $\mu g/m^3$) intensity and intermittent frequency:

$$0.5 \times 770\ \mu g/m^3 + 0.5 \times 550\ \mu g/m^3 = 660\ \mu g/m^3.$$

The relative contributions of inhalation and dermal PCB exposures were set to equal importance and this resulted in the dermal-JEM and inhalation-JEM being highly correlated (Pearson correlation coefficient 0.91).

Table 5 presents the JEM. The inhalation exposure levels have units of $\mu g/m^3$ whereas the dermal exposure levels and the average PCB exposure level are unitless, i.e.; only relative scores are associated with exposure. The intensity rating assigned in Step 6 is denoted 1°, and the second intensity ratings given to exposure categories with intermittent frequency (Step 9) were denoted 2°.

Cumulative PCB exposures for the epidemiological analysis were estimated using intensity, frequency, PCB-era factor, and duration in a job. A worker’s cumulative exposure to PCBs was calculated by summing workday exposure for the entire work history, and converting days to years, yielding a value in $\mu g/m^3$/year for inhalation or unitless/year for dermal JEM. Cumulative exposure ranged from 4,550 to 9,650,000 unit-days, median 127,000 unit-days. Cut-off points at 92,900 and 595,000 unit-days of exposure defined tertiles with equal numbers of deaths.

Discussion

We developed period-specific inhalation and dermal JEMs based in part on process descriptions and industrial hygiene data for all jobs from 1938, when the manufacture of PCB-filled capacitors began at this plant, through 1977 when work histories were obtained. The JEMs have been used in a mortality study combining two capacitor cohorts [4], and in a neurodegenerative mortality disease study[10] where three PCB cohorts were combined. Combining cohorts from different plants was possible because differences in exposure levels between plants were taken into account by the JEMs. Comparing the plant-specific JEM described here with the JEM developed for former capacitor workers in Indiana, there was a 7.5 times higher cumulative exposure at this plant compared with the Indiana (median 16,860 unit-days[11]) plant. Using plant specific JEMs will reduce misclassification of cumulative exposures in epidemiological studies, as well as providing better estimates of exposure-response relationships.

Ideally, a validation of the JEMs would be carried out by measuring current PCB air concentrations and comparing the JEM categories with these concentrations not used for the development of the JEMs. Even though a validation of the JEM was not possible because the plant was declared a toxic waste site, it is reassuring that cumulative exposure-response relationships were found in both epidemiological studies[4, 10].

Job titles with different PCB exposure patterns were sometimes assigned to a single job code in the work histories. One such example was "welding" or "soldering"; however, welding was done prior to PCB filling in the Pre-Assembly and soldering was performed after impregnation while the capacitors were covered in PCBs. Unique combinations of job codes and department codes revealed appropriate departments and hence these jobs were split and assigned to two exposure categories (cat. 20 and 24). This method was used on an additional six jobs to reflect differences in PCB exposures. Adjustments for ventilation and personal protective equipment were not made. Available ventilation information was insufficient to distinguish one job task as being more or less ventilated than another. Few workers wore gloves, aprons, safety glasses or respirators (NIOSH 1976). Ordinary street clothes were worn to work and no clothes washing facilities were available at the plant. PCB exposures could potentially increase among workers who did not regularly wash their contaminated clothes.

The purpose of the JEM is to define similar exposure groups (e.g., a group of employees having similar exposure profiles) which can be used to evaluate relationships with health outcomes in later epidemiological analyses[12]. To assess all job tasks quantitatively, assumptions were made. It was assumed that similar job tasks performed using similar materials and in the same location would give rise to similar exposures, and that air sampling results for a few workers could represent the exposure for the rest of the JEM category. These assumptions were necessary to assign scores to the categories since not all workers with different tasks were sampled. The accuracy of the scores assigned to the JEM exposure categories cannot be measured.

Even though there were only eight combinations of intensity and frequency of PCB exposure ratings we decided to keep all 29 job exposure categories, because additional exposures were different for some categories with the same ratings. For example, repair and salvage workers (cat 19) and solderers (cat 24) were rated intermittent high for inhalation and continuous high for dermal PCB exposures; however, solderers were also exposed to soldering fumes, while repair and salvage workers were not exposed to these additional chemicals. By keeping categories with additional chemical exposures separate, the epidemiologists could exclude workers with additional chemical exposures in their analysis. This is particularly important when other carcinogenic agents or chemicals that might alter the uptake or metabolism of PCB in the body were present. This was done in a sensitivity analysis; workers exposed to TCE were excluded to determine if TCE exposure affected the results (it did not).

About two thirds of the air concentration measurements used to assess exposure intensity for the exposure categories were area air concentrations collected in a fixed location. Assumptions associated with using the area air concentrations were that the concentrations were representative of emissions from a process and the PCB exposure of the workers who worked in the immediate vicinity of the process. Assumptions about the personal air concentrations were also made: that there were no significant inter-worker differences and that the day the air concentrations were collected did not differ significantly from other workdays. In addition, the assumption was made that the concentration measured over a short time would be representative of concentration during the full shift.

The majority of the air concentrations were collected during the NIOSH survey in 1976 (95/112 samples)[8]. The strategy for this industrial hygiene survey was two-fold: (1) to collect samples in the three highest PCB-exposed departments, and a few in the low PCB-exposure departments for comparison (high- and low-exposed departments being defined by the then - current industrial hygienist using expert judgment) and (2) to compare results for two PCB collection methods (Florisil and impinger). The company collected PCB samples (1976) using a surveillance strategy of high exposed workers/ areas. This is why it was important to assess all jobs based on exposure determinants, and use the air concentrations to assign intensity scores, not vice versa.

Assigning the same mean exposure to all individuals in one category will result in some unknown amount of exposure misclassification. This is especially true of high and medium exposures where the air concentrations overlapped. Creating exposure categories based on similarity of exposure determinants, and using the limited air concentration data to anchor these exposure ratings were attempts to reduce misclassification of exposures. Codes for departments missing descriptions were especially prone to misclassification. The assumption that exposures were higher in the earlier time period could also be a source of misclassification.

It was not possible to evaluate systematic differences in exposure between individuals within a given job category, given the limited data available. In addition, the relative contribution of dermal and inhalation exposures was not known, which could also lead to a bias in the exposure estimates. Lees *et al*. (1987)[13] compared inhalation and dermal exposure of transformer maintenance and repairmen to PCB using wipe samples and air concentrations, and assumptions of frequency of task and surface area of workers' hands. The evidence they presented supports the hypothesis that for persons occupationally exposed to PCBs, the dermal and dermal-oral exposure routes were the predominant contributors to body burden, although the authors did not say how much more predominant the dermal route was compared to inhalation. Our approach to this issue was to keep the two routes of administration within the same scale because the assessment was done separately for dermal and inhalation exposure.

Conclusions

We developed a job exposure matrix for retrospective epidemiologic cohort studies using the approach of categorization by similar exposures[14]. Minimum requirements for historical industrial hygiene data needed to develop a JEM have not been established, nor have standardized methods. We judged the data we had to be sufficient to develop a JEM, and to minimize exposure misclassification, a comprehensive approach incorporating information about tasks, activities, work locations, process descriptions, job titles, lay-out of work areas, air concentrations from the late era, usage of PCB mixtures, and industrial hygiene data was used. Such JEMs allow workers to be classified by their cumulative estimated exposures rather than their duration of employment.

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