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Environmental determinants of polychlorinated biphenyl concentrations in residential carpet dust

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Abstract

Polychlorinated biphenyls (PCBs), banned in the United Sates in the late 1970s, are still found in indoor and outdoor environments. Little is known about the determinants of PCB levels in homes. We measured concentrations of 5 PCB congeners (105, 138, 153, 170, 180) in carpet dust collected between 1998–2000 from 1,187 homes in four sites: Detroit, Iowa, Los Angeles, and Seattle. Home characteristics, occupational history, and demographic information were obtained by interview. We used a geographic information system to geocode addresses and determine distances to the nearest major road, freight route, and railroad, percentage of developed land, number of industrial facilities within 2 km of residences, and population density. Ordinal logistic regression was used to estimate the associations between the covariates of interest and the odds of PCB detection in each site separately. Total PCBs levels (all congeners < maximum practical quantitation limit [MPQL] vs. at least one congener ≥ MPQL to < median concentration vs. at

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Supporting information **available**
Additional tables have been added to supplement the primary analyses of this paper. This information is available free of charge via the Internet at http://pubs.acs.org/.

least one congener >median concentration) were positively associated with either percentage of developed land (OR_{range}: 1.01-1.04 for each percentage increase) or population density (OR: 1.08 for every 1,000/mi^2) in each site. The number of industrial facilities within 2 km of a home was associated with PCB concentrations; however, facility type and the direction of the association varied by site. Our findings suggest that outdoor sources of PCBs may be significant determinants of indoor concentrations.

Introduction

Polychlorinated biphenyls (PCBs) are man-made compounds found in older electrical equipment, hydraulic machinery, fluorescent lighting fixtures, and numerous construction materials such as plasticizers, adhesives, flame retardants, caulk, and paints[1-3]. Ecological concerns, the probably carcinogenicity of PCBs[4], and links to diseases of the immune, reproductive, nervous and endocrine systems led to the banning of manufacturing and use of PCBs in the United States in 1977 and 1979, respectively [3]. However, PCBs remain environmental contaminants due to their persistence and bioaccumulation through the food chain. PCBs are found in many older buildings and can persist for long periods of time indoors because they are not susceptible to environmental and microbial degradation[5-6]. In fact, despite cessation of use for several decades, there has been little change in PCB concentrations in indoor air, where levels can be approximately 30 times higher than in ambient air[7]. These findings are important given that people of all ages spend up to 90% of their time indoors [8-9].

A recent study of 24 schools, residential and other public use buildings in the Boston area found that 33% contained caulking-material with PCB content exceeding 50 ppm[10], the established EPA limit for PCBs in construction materials and other non-liquid products. The breakdown of construction materials, especially in buildings constructed in the middle part of the 20th century in which PCB concentrations were found to be highest [2,5,11], may act as a source of PCB emissions to indoor and ambient environments. While many sources of PCBs in the indoor environment have been identified, the characterization of these sources remains incomplete [12].

Many studies have found higher atmospheric and soil PCB levels associated with greater proximity to urban centers, particularly industrial complexes [13-22]. Specifically, industrial complexes such as waste facilities, coal-fired power plants, and various types of incinerators have been identified as PCB sources in the U.S.[20] and worldwide [21,23-26]. Electrical and power equipment, hydraulic machinery and other materials that may contain PCBs are also found along roads and within rail-yards, which have been identified as areas with PCB contamination[27]. In addition, roads may facilitate PCB dispersion by serving as corridors for transportation of contaminated soils by wind [28]. Soils act as a major reservoir and sink for many persistent organic pollutants (POPs), including PCBs [29]. Therefore soil-air exchange processes, such as deposition and volatilization, may also be relevant to the movement of PCBs in the environment [14].

PCBs persist in carpet dust due to their resistance to degradation, semi-volatile nature, and high propensity to bind to particles [29-31]. Levels in carpet dust may therefore be a good measure of long-term indoor exposures [30,32]. Specifically, ingestion and inhalation of carpet dust may represent relevant exposure pathways [33]. House dust may also be an especially important source of exposure for small children as it represents a greater proportion of overall PCB exposure in toddlers (6-24months) than adults [33]. Using carpet dust as an exposure metric higher PCB concentrations were associated with an increased risk of non-Hodgkin lymphoma (NHL) in the National Cancer Institute's (NCI) Surveillance, Epidemiology and End Results (SEER) NHL case-control study (NCI SEER-NHL study) [2]. In light of the potential health risks associated with PCBs and the importance of dust as an exposure pathway, we sought to identify home and community characteristics, demographic, and environmental factors that may be determinants of PCB levels in carpet dust samples collected in the NCI SEER-NHL study.

Materials and Methods

Study Population

The NCI SEER-NHL study is a population-based case-control study in 4 areas covered by SEER cancer registries: Detroit, Michigan metropolitan area (Macomb, Oakland, and Wayne counties); state of Iowa; Los Angeles County, California; and Seattle, Washington metropolitan area (King and Snohomish counties) [34]. The study population has been described in detail previously [2,34-35]. Briefly, cases were men and women aged 20 – 74 years newly diagnosed with a first primary NHL between July 1998 and June 2000. Of the 2,248 potentially eligible cases, 320 (14%) died before they could be interviewed, 127 (6%) could not be located, 16 (1%) had moved away, and 57 (3%) had physician refusals. Of the 1,728 remaining cases, 1,321 (76%) participated. Controls were selected from the general population using random digit dialing (<65 years) or from Center for Medicare and Medicaid Services files (≥ 65 years) and were frequency matched to cases by age, sex, race, and study site. Of 2,046 eligible controls, 1,057 (52%) participated. The study was approved by the human subjects review boards at all participating institutions, and written informed consent was obtained from each participant.

Computer-assisted personal interviews were conducted in each participant's home. Interviewers asked about housing type, age of the home, number of rooms that were usually vacuumed with the sampled vacuum cleaner, and presence of oriental rugs. Complete occupational histories and demographic information on race and education were also obtained.

Dust samples and laboratory analysis

As described in detail previously [2,34], dust was collected between February 1999 and May 2001 from vacuum cleaners of participants who gave permission (93% of cases, 95% of controls) and who had used their vacuum cleaner within the past year and owned at least half their carpets or rugs for 5 years or more (695 cases [57%], 521 controls [52%]). Dust samples from 682 cases (98%) and 513 controls (98%) were successfully analyzed between September 1999 and September 2001.

We analyzed 2 g dust aliquots for 5 PCB congeners (105, 138, 153, 170, 180) using gas chromatography/mass spectrometry (GC/MS) in selected ion monitoring mode; concentrations were quantified using the internal standard method. The congeners were chosen because they are among the most commonly detected in house dust [36]. The usual detection limit (UDL) was 20.8 ng/g, although samples weighing <2 g had slightly higher detection limits. We defined a maximum practical quantitation limit (MPQL), specific to each congener, as the concentration above which all samples could be quantified (Table 1). To describe the distribution of PCBs (Table 1), but not in other analyses, we used an imputation procedure[2,34] to estimate concentrations that were below the usual limit of detection.

Efficient extraction of PCBs was demonstrated by measurement of 27 laboratory-spiked dust samples [2]. Measurements of PCBs in terms of detection/non-detection in duplicate samples were in close agreement, ranging from 92.6% (PCB 153) to 100% (PCBs 105, 170). Coefficients of variance (CV) for samples measured in duplicate with concentrations above the usual detection limit ranged from 0.04 (PCBs 153, 170) to 0.21 (PCB 138), indicating good precision. Identification of analytes was confirmed by full-scan GC/MS on 55 samples [2].

Residential Locations

Geographic coordinates for residences were obtained by geocoding addresses using a modified Microsoft Visual Basic version 6.0 program (TeleAtlas, Lebanon, NH) to match input addresses to the TeleAtlas MatchMaker SDK Professional version 4.3 street database. Additionally, interviewers took a global positioning system (GPS) reading outside the participant's home using a Garmin GPS12 Personal Navigator (Garmin International, Inc., Olathe, KS). Coordinates for residential addresses were assigned from GPS readings if the distance between GPS and geocoded coordinates was <200 m. Discrepancies between GPS and geocoded coordinates ≥200 m were visually checked using mapping software (ArcMap, ESRI, Redlands, CA) and web-based aerial photographs (http://maps.google.com/). Of the 1,195 homes with dust measurements, 1,074 (89.9%) residential locations were assigned from GPS coordinates, whereas 113 (9.5%) were geocoded coordinates. Eight homes (0.7%) could not be accurately located and were excluded, for a total of 1,187 homes in our analyses.

Land Cover

The percentage of developed land around homes was determined for circular buffers from 1 to 20 km in radii, in 1 km increments using the U.S. Geological Survey's 2001 National Land Cover Database (NLCD 2001). NLCD 2001 is a 30 m resolution land cover database created from Landsat 5 and Landsat 7 satellite imagery that identifies 4 categories of developed land: open space (<20% impervious surface), low intensity (20% – 49% impervious surface), medium intensity (50% – 79% impervious surface), and high intensity (≥80% impervious surface). Land cover classified as low to high intensity was used to calculate the proportion of developed land around each home in final analyses. Other calculations of developed land, such as medium plus high intensity, did not improve model fit (results not shown). We evaluated both cumulative and non-overlapping buffers. We selected the buffer size for use in final models by considering a model with many buffers of increasing size and models with only single buffer sizes (distances of 1 to 20 km). A 2 km cumulative buffer was selected because it was the most strongly and significantly associated with PCB levels. Buffer analyses were performed in the R computing environment (R Development Core Team, 2010).

Proximity to Industrial Facilities, Roads and Railroads

We used the U.S. Environmental Protection Agency (EPA) Toxics Release Inventory (TRI)[37] to calculate the number of industrial facilities within 20 km of each residence. Final models included counts of these facilities within a 2 km buffer to remain consistent with the developed land variable and because there were few industrial facilities within 1 km of residences. Addresses and coordinates of industrial facilities reporting to the TRI from 1990 – 1999 were tabulated by two-digit standard industrial classification (SIC) code. Similarly, we included a separate count of dioxin-emitting facilities, some of which release PCBs and PCB-like compounds[38], within 2 km of residences using an EPA national database [39] that included municipal solid waste incinerators, medical waste incinerators, sewage sludge incinerators, hazardous waste incinerators, cement kilns burning non-hazardous waste, cement kilns burning hazardous waste, and coal-fired electric generating plants.

Distances from residences to the nearest major roads and freight routes were calculated from the TeleAtlas Dynamap Transportation version 5.2 (2003) and defined as arterial roads of the inter-state, inter-metropolitan area, or intra-state/intra-metropolitan area/inter-metropolitan area. Freight routes, which can include major roads, are any roads permitting trucks (Freight Analysis Framework 2.2 Network Machine Readable Data Files, Federal Highway Administration Office of Freight Management and Operations, Washington DC, 2009). Distance from residences to the nearest railroad (up to 20 km for consistency with other buffer variables) were calculated from the National Atlas of the United States database (2005) [40].

Occupational PCB Exposure

We evaluated occupational exposure to PCBs as a potential source of PCBs in the home. Trained interviewers administered complete occupational history questionnaires, described in detail previously[41]. Each job was coded for occupation and industry using 1980 SOC codes[42] and 1987 SIC codes[43], respectively. An industrial hygienist reviewed the PCB literature to identify occupations and industries with possible PCB exposures. This information was used to assign an initial probability of PCB exposure [not exposed (<5% of workers likely exposed), possibly exposed (5-<50% of workers likely exposed), and probably exposed (≥50% of workers likely exposed)] to each job that participants held while living in the home where dust was collected. Probability estimates for each possibly and probably exposed job (e.g., electricians, electrical and electronic equipment repairers and technicians) were reviewed using additional occupational questionnaire information and revised if needed. Final probability estimates were categorized as: not exposed (never worked in a possibly or probably exposed job, including no job), possibly exposed (ever worked a possibly exposed job and never worked a probably exposed job), and probably exposed (ever worked a probably exposed job).

Statistical Analysis

We evaluated the relationship between covariates of interest and detections and concentrations of PCBs in carpet dust using multivariable logistic regression models with separate models for each study site. We do not present an all-sites model because certain factors, such as specific industrial facilities, were not substantially present in all sites. Moreover, variables such as type of home may not be comparable across sites.

We constructed models using two different approaches. First, we used ordinal logistic regression to model the sum of the five congeners (total PCBs) categorized as low (no congener detected above MPQL), medium (at least one congener detected above the MPQL but below the median concentration) and high (at least one congener above the median concentration). The parameter estimates from ordinal logistic models are based on the proportional odds assumption, which states that the relationship between the covariates and each outcome level is the same. The assumption of proportional odds (α=0.05) was tested and met, using a chi-sq score test (not shown). In our analyses of total PCBs, parameter estimates are interpreted as the log odds of observing a higher PCB level (low/medium/high) for each unit increase of a covariate. Second, we used logistic regression to estimate the associations between the covariates of interest and the odds of detection for each PCB congener. Our analyses focus on the most commonly detected congeners: PCBs 138, 153 and 180. Model results for PCB 105 and 170 are presented in a supplemental table.

We considered several individual-level covariates as potential determinants of household PCB levels. Characteristics of the study homes were: year home was built (<1940, 1940-1979, 1980+), type of home [single family, other (including apartments, townhouses, duplexes, mobile homes)], number of rooms usually vacuumed (1-5/6+), and the presence of oriental rugs (yes/no). To account for potential PCB infiltration from surrounding neighborhoods we investigated census block characteristics from U.S. Census 2000: median income, population density (1,000 persons/mile^2), and median year residences were constructed (<1940, 1940-1979, 1980+). Distances to major roads, freight routes and railroads were categorized by tertiles. Occupational exposure to PCBs (not exposed/possibly exposed/probably exposed), as previously defined, participant's race (white, black, other) and education level (<12yrs, 12-15yrs, 16+ yrs) were also investigated in each model. We evaluated total numbers of TRI facilities and dioxin-emitting facilities as separate variables in models. We used a backward stepwise selection of covariates with an α=0.10 criterion for inclusion. Odds ratios (ORs) and 90% confidence intervals ($p \leq 0.1$) were calculated using SAS statistical software version 9.1 (SAS Institute, Inc., Cary, North Carolina). All p-values are 2-sided.

After considering total numbers of TRI facilities, we further examined TRI facilities by 2-digit SIC. Counts of facility types by SIC that were statistically significant at $p \leq 0.10$ in individual models and were highly correlated at each site (r>0.65) were summed [e.g., the number of food and kindred product facilities (SIC 20) and electronic and other electric equipment (SIC 36) facilities were summed to a single variable in Seattle models]. The decision to include either the total number of TRI facilities or the number of facilities with a specific SIC was based on which model explained the highest degree of variability, where applicable. Individual dioxin emitting facilities were not investigated due to the small number of facilities near residences.

For each study site, we used generalized additive models[44] (GAMs) with a spatially smoothed term to determine if there was significant residual spatial variation in total PCBs after adjusting for the final covariates determined from ordinal logistic models. We used a thin plate regression spline[45] to smooth over the spatial coordinates of the residential locations of the PCB samples to estimate the residual spatial component of PCB risk. We did not observe significant residual spatial variation; therefore, we present results from the logistic models. GAM parameters were estimated using the package mgcv version 1.7-6 (http://cran.r-project.org/web/packages/mgcv) in the R computing environment [46].

Results

Table 1 shows the percentage of dust samples with measurements above the UDL and MPQL for each PCB congener for all study sites combined and separately. Overall, the percent of samples with concentrations greater than the UDL ranged from 13% (PCB 170) to 38% (PCB153). The highest PCB concentrations and most frequent PCB detections generally occurred in the Detroit study area. One exception was PCB 180, which was detected more frequently and at higher concentrations in the Seattle area. PCB detections and concentrations were lowest in Los Angeles County. In all locations, PCB 153 was the most frequently detected congener and PCB 170 was detected in the fewest samples and at the lowest concentrations.

The frequency distributions of total PCBs (low, medium, high) by covariates of interest are shown in Table S1. The frequency of detections above the MPQL (medium and high categories combined) was greatest for homes built between 1940 and 1979 in Detroit and Seattle, whereas detections were greatest for homes built before 1940 in Iowa and Los Angeles. More single family homes had PCBs above the MPQL compared to other housing types. In all sites, residences with more developed land within 2 km had more frequent PCB detections. Similarly, having one or more industrial facilities within 2 km was associated with more frequent PCB detections at most sites.

Shown in Table S2, the highest median percentage of developed land around homes was in Los Angeles (90.3%), followed by Detroit (80.6%), Seattle (58.5%) and Iowa (17.6%). More than half of homes in Iowa and Seattle had no industrial facilities within 2 km.

Tables 2 to 5 provide parameter estimates and 90% CI for significant (α=0.10) determinants of total PCBs and PCB congeners 138, 153, and 180 from multivariable models for each study site.

Detroit

In Detroit homes (Table 2), the odds of higher PCB levels (e.g., high versus medium or medium versus low) increased by 2% (OR=1.02; 90% CI, 1.01-1.04) for each percent increase of developed land within 2 km of homes. Conversely, the total number of industrial facilities within 2 km was inversely associated with total PCB levels (OR=0.88; 90% CI, 0.78-0.98). The odds of higher PCB levels decreased with the number of rooms and increased with 12 or more years of education, compared to those with less than 12 years.

Many variables showed similar associations in one or more congener-specific models (Table 2). However, specific industrial facilities were more strongly associated with detections of individual congeners than the total number of industrial facilities and we observed both positive and inverse associations. Increasing numbers of publishing/printing facilities were associated with lower detections of PCBs 138 and 153. In contrast, the number of miscellaneous manufacturing was associated with increased odds of detecting PCB 153. Having held a job with probable PCB exposure increased the odds of PCB 180 detection. The distance from freight routes and railroads was associated with increased odds of detections of PCB 138 and 153, respectively; however, the relationship was not monotonic. In addition, increasing numbers of electronic/electrical equipment facilities was associated with significantly decreased odds of detecting PCB 105 (Table S3). Whereas, the number of national security facilities was associated with increased odds of detection of PCB 170 (Table S3).

Iowa

Among Iowa homes, the percentage of developed land within 2 km was positively associated with total PCB levels (OR=1.01; 90% CI, 1.00-1.02) (Table 3). Homes at an intermediate distance from railroads (1,419-3,774 m) were 2.2 times more likely to have higher total PCB levels than homes at closer distances. Compared to single family homes, other home types had significantly lower proportional odds. The odds of higher total PCBs decreased among Iowa participants with more than 12 years of formal education compared to those with less than 12 years.

In congener-specific models, additional factors were significant predictors of PCB detections. The odds of detecting PCB 180 increased with the number of industrial machinery and equipment facilities near homes (Table 3) and the odds of detecting PCB 105 and 170 increased with increasing numbers of fabricated metal product facilities within 2 km (Table S3).

Los Angeles

Similar to Detroit and Iowa, the percentage of developed land within 2 km of homes in Los Angeles was associated with increased odds of higher total PCB levels (OR=1.04; 90% CI, 1.01-1.06) (Table 4). The number of industrial facilities from several industrial sectors (food and kindred products, furniture, stone, clay and glass products, and primary metal industries) within 2 km of homes was associated with lower PCB levels (OR=0.92; 90% CI, 0.88-0.97). Increasing distance between a home and the closest major road was inversely associated with total PCB levels and the odds of detection of all congeners except PCB 170. Homes in which a participant held an occupation with probable PCB exposure were more likely to have higher PCB levels.

In congener-specific models, the odds of detecting PCBs decreased with increasing industrial facilities within 2 km of homes; however, the type of industrial facilities varied by congener (Table 4). The odds of detecting individual congeners increased with decreasing

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distance between a home and the closest major road. The number of dioxin facilities was associated with increased odds of detecting PCB 180 and probable occupational exposure was associated with increased odds of detecting PCB 153.

Seattle

Among homes in Seattle, population density demonstrated a stronger positive association with total PCB levels (OR=1.08; 90% CI, 1.01-1.14) than percentage of developed land (Table 5), although percentage of developed land and population density were positively correlated (r=0.64). The number of food/kindred products and electronic/other electric equipment facilities combined, as well as the number of industrial machinery and equipment facilities, were positively associated with total PCBs (OR=1.22; 90% CI, 1.04-1.43 and OR=2.13; 90% CI, 1.33-3.41, respectively). Homes in census block groups where the median housing age was 1980 or later had significantly lower odds of higher PCB levels than homes in block groups where most structures were built before 1940. We observed similar predictors of PCB detections in congener-specific models with the exception that percentage of developed land, as opposed to population density, was significantly associated with detection of PCB 105 (Table S3).

Discussion

This is one of the few U.S. studies to investigate the relationship between characteristics of the home and built environment and indoor PCB concentrations. In this large multicenter study, the most consistent determinant across all study sites was the density of the built environment, i.e. percentage of developed land or population density around a home. Both percentage of developed land within 2 km of a home (Detroit, Iowa, Los Angeles) and block group population density (Seattle) were positively associated with total PCB levels and with detections of most congeners. The relationship between proximity to industrial facilities and PCB levels varied considerably by type of facilities and site. In addition, patterns differed somewhat among the congeners. The total number of industrial facilities within 2 km of homes was inversely associated with PCBs in Detroit and Los Angeles (approximately 8-12% decreased odds of PCB detection for every facility within 2km), but was not associated with PCBs in Iowa and Seattle. However, with the exception of Los Angeles, the density of specific industry types, including industrial machinery/equipment, food/kindred products and electronic/other electric equipment facilities and manufacturing facilities, were generally positively associated with PCB detections (OR_{range}: 1.22-3.83) in one or more sites.

PCB concentrations varied by study site, which is consistent with the high degree of geographic variability in PCB concentrations in the United States [47] and worldwide[33]. Studies in many geographic locations have observed higher soil and air PCB concentrations near urban centers compared to more rural areas. Atmospheric PCB concentrations measured in urban Chicago, IL were greater than concentrations in surrounding rural areas[20]. Urban-rural differences have also been reported worldwide. Atmospheric PCB concentrations increased with proximity to the urban center in the Toronto, Ontario metropolitan area[18-19]. Atmospheric and soil PCB concentrations from samples taken along an urban-rural transect in the West Midlands of the U.K. increased with greater proximity to the urban center[17]. Similar patterns have also been observed in Taiwan[21] and Korea[22].

Higher levels of PCBs in developed and urban areas are likely a function of a greater density of PCB sources in these areas. Sources include plasticizers, flame retardants, caulk, and electrical equipment, which are likely to be found in greater quantities in older neighborhoods or areas with industrial sources. Additional sources of PCBs include landfills and waste-handling facilities, which are typically located in and around urban areas[16]. Decay and weathering of PCB-containing materials as well as volatilization from contaminated sources[13] may result in PCB-containing particles that can be readily transported through air or other media. However, the relationship between outdoor PCB sources and indoor PCB levels is complex, as illustrated by the observation that indoor air PCB concentrations in homes near PCB contaminated areas along the Hudson River were similar to levels in homes in areas with lower outdoor air PCB concentrations[48].

Several studies have reported elevated levels of PCBs around certain industrial facilities. High levels of PCBs in air have been measured within approximately 1-8km of steel manufacturing facilities and petrochemical complexes in Korea[23] and Turkey[14,24]. Similarly, PCB measurements in air were high near a petroleum refinery in southern Taiwan[21] and within air and dust samples taken around a transformer recycling workshop in China[25]. Levels of PCBs may be higher around certain industrial facilities due to contamination of the site, PCB-containing materials within the infrastructure or emissions from combustion of PCB-containing materials.

Certain industrial facility types were significant determinants of higher PCB levels in some study sites (e.g., fabricated metal products in Iowa and industrial machinery and equipment in Seattle). The number of specific facility types varied by site, which may explain some of the different associations we observed by site. In some sites, we observed inverse associations between the number of industrial facilities and PCB levels. The explanation for findings of inverse associations is unclear, with the caveat that all findings are subject to chance. A previous study in Chicago found that industrial complexes were sources of atmospheric PCBs, but they were not substantial contributors to atmospheric concentrations in surrounding areas based on dispersion modeling over an approximately 70 mile transect[20]. Similarly, relatively low concentrations of PCBs have been measured in residential and rural air approximately 4 to 12km or more from industrial complexes in South Korea[23]. These findings demonstrate that PCBs from industrial sources may contribute to surrounding areas in a highly variable manner.

In Los Angeles, homes within about 500 meters of major streets were more likely to have higher levels of PCBs than homes at greater distances. However, for freight routes and railroads in the Detroit area and railroads in Iowa, an intermediate distance was associated with higher PCB levels in homes. PCBs have been detected in street dust in Buffalo, NY[28], which may arise from local sources or more distant atmospheric dispersion and transported along roads. Infrastructure associated with railroads, such as rail transformers, may still contain PCB contaminated materials that can act as sources to the local environment[27]. However, there may be complex patterns of transport along roads and railroads that we failed to capture with a closest distance metric. Simple Euclidean distances to roads, railroads and industries, do not completely characterize the spatial pattern around a home. For example, a home may be near a single road or railroad or close to a network of roads/ railroads. Additionally, we did not address wind patterns, which can play an important role in the transport of PCBs [28], in relation to roads or railroads and other potential sources of PCBs.

No residual spatial variability was observed in GAM analyses, suggesting that the variability in PCB levels not accounted for by model covariates is likely due to small scale patterns, such as sources in and around the home. Indoor sources may contribute to outdoor PCB levels, which may then re-enter the home. We were unable to fully capture the dynamic exchange between indoor and outdoor PCBs at the level of individual homes, beyond assessing environmental features around a home and a few select home characteristics.

Numerous products used in home construction, such as caulking and joint sealants[10,49-50], that have historically contained PCBs can act as sources to the indoor environment. Paints and electrical equipment with small capacitors[51-52], fluorescent lights[48], and wood floor finishes used in the 1950’s -60’s[1] have also been identified as potential sources of PCB exposure in the home. The home characteristic measures available in this study (age of home, housing type, and number of rooms with carpet) do not specifically characterize in-home sources of PCBs and fail to capture renovations, age of PCB-containing materials in a home, or the type of construction material (e.g. wood vs. brick). Renovations such as replacement of home flooring have been associated with higher levels of PCBs in the home[53]. Thus, it was not unexpected that these general home characteristics were identified as significant determinants only in some models, as any one factor is unlikely to explain a substantial portion of variability in indoor PCB levels.

Previous analysis of dust PCB concentrations among controls in the NCI-SEER NHL Study found a positive association with age of the home, with the highest levels in the older homes[2]. This association did not remain in our site-specific analyses after controlling for additional environmental variables. Only in Seattle was median housing age in the census block group a significant determinant of individual home PCB levels. Some[32,53-55], but not all[56], studies have observed higher PCB levels or exposures associated with older homes. The number of rooms usually vacuumed demonstrated an inverse association with PCB levels in the Detroit study area. Assuming that there is a relatively high correlation between number of rooms and home size, this finding would be consistent with a previously observed inverse association between residence square footage and concentrations of environmental contaminants in house dust[57].

Interestingly, PCB levels were positively associated with education level in the Detroit area, inversely associated in Iowa, and there was no observed association in Los Angeles County and Seattle. Beyond chance findings, a possible explanation is that education level may be associated with in-home behaviors or other unmeasured factors that may influence track-in or in-home release of PCBs. A recent study in California found that residents employed as electricians or in industrial operations had higher PCB levels in their homes[53]. Our analysis showed increased PCB levels in Detroit and Los Angeles were associated with participants who worked in jobs with probable PCB exposure, in spite of the small number of participants employed in these occupations (n-17) Although, the number of homes with occupationally exposed residents may be underestimated because we only had occupational information on study participants and not other residents of a home.

A limitation of our analyses is a lack of information to characterize actual sources of PCBs, both in the home and outdoor environment. The factors we investigated are proxies for hypothesized sources. The transport of PCBs through the environment involves complex processes that can be affected by many factors including meteorological conditions and topography. We did not have information on historic use of PCBs by facility nor did we have information on sources of PCBs within the infrastructure or the condition of facility infrastructure. Additionally, our analyses were based on only one dust measurement, which does not capture potential within-home temporal variability. However, dust has been shown to be a long-term measure for persistent chemicals[58] and low variability in PCB levels has been observed with repeated dust samples within a home[59]. The relatively high detection limits limited statistical power to detect associations with covariates. The number of facilities within specific industrial sectors varied by site and limited our power to evaluate associations in instances where counts were low. We also included only industrial facilities reported in TRI or the EPA dioxin database, which may not capture all industrial PCB sources. Finally, the large number of variables and models considered increases the change type I error may occur and caution should be applied when interpreting the data.

Strengths of this study included the use of a large number of carpet dust PCB measurements from the NCI SEER-NHL study, which allowed us to compare potential determinants in four geographically diverse U.S. locations. Based on associations between PCB levels and proximity to urban centers observed in previous studies [17-22], we attempted to quantify urbanicity by calculating the proportion of developed land around individual homes. We also investigated the density of a wide range of industrial facilities and dioxin-emitting facilities around each home. Finally, given the size and geographic extent of the NCI SEER-NHL study, we were able to simultaneously investigate many attributes of the built environment and industrialization around a home in addition to characteristics of the home itself as they relate to indoor carpet dust PCB levels.

In summary, we identified several possible determinants of PCB levels in carpet dust, most of which were related to the built environment around a home. We had limited ability to evaluate specific in-home characteristics, which likely contribute substantially to indoor levels. However, our findings suggest that, in addition to indoor sources, infiltration and potential track-in of PCBs from outdoors may be significant determinants of indoor PCB concentrations.

Supplementary Material

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Table 1

Detection percentages and distribution of PCBs in household carpet dust samples from the NCI SEER-NHL Study, 1998-2000

Study area and PCB congener	# Samples ≥ UDLs[a] (%)	# Samples ≥ MPQL[b] (%)	Median (ng/g) among homes with detections	Concentration (ng/g)			
				Percentile[c]			
				25th	50th	75th	95th
All sites (n=1187)							
PCB 105	211 (17.8%)	71 (6.0%)	42.4	1.2	4.2	14.0	79.3
PCB 138	369 (31.1%)	162 (13.7%)	47.4	2.5	8.4	27.7	191.0
PCB 153	449 (37.8%)	187 (15.8%)	46.6	3.2	11.6	34.6	201.0
PCB 170	157 (13.2%)	51 (4.3%)	42.6	0.4	1.9	7.3	48.4
PCB 180	298 (25.1%)	105 (8.9%)	44.2	1.8	6.1	20.9	103.0
Detroit (n=204)							
PCB 105	48 (23.5%)	21 (10.3%)	55.7	1.5	5.8	19.1	156.0
PCB 138	84 (41.2%)	41 (20.1%)	49.8	3.4	15.4	38.2	359.0
PCB 153	103 (50.5%)	46 (22.6%)	51.6	5.4	21.1	52.0	368.0
PCB 170	32 (15.7%)	11 (5.4%)	42.6	0.6	2.4	11.8	60.1
PCB 180	58 (28.4%)	24 (11.8%)	44.7	2.1	6.9	24.2	103.0
Iowa (n=342)							
PCB 105	60 (17.5%)	17 (5.0%)	37.6	1.3	4.2	12.7	69.9
PCB 138	102 (29.8%)	40 (11.7%)	39.8	2.6	8.0	26.2	129.0
PCB 153	123 (36.0%)	45 (13.6%)	42.8	3.2	9.8	30.8	154.0
PCB 170	39 (11.4%)	16 (4.7%)	43.5	0.4	1.7	6.1	48.0
PCB 180	82 (24.0%)	27 (7.9%)	41.7	1.9	6.0	20.0	99.0
Los Angeles (n=295)							
PCB 105	32 (10.8%)	5 (1.7%)	33.3	1.1	3.9	10.5	34.7
PCB 138	47 (15.9%)	16 (5.4%)	36.2	2.1	6.1	16.0	59.1
PCB 153	64 (21.7%)	17 (5.8%)	34.7	2.6	7.6	19.6	64.3
PCB 170	22 (7.5%)	7 (2.4%)	37.1	0.4	1.9	5.4	27.9
PCB 180	41 (13.9%)	12 (4.1%)	43.7	1.7	5.1	13.4	53.0
Seattle (n=346)							
PCB 105	71 (20.5%)	28 (8.1%)	45.8	1.0	3.8	14.3	107.0
PCB 138	136 (39.3%)	65 (18.8%)	54.7	2.1	11.0	42.4	256.0
PCB 153	159 (46.0%)	79 (22.8%)	56.3	3.1	15.1	49.8	273.0
PCB 170	64 (18.5%)	17 (4.9%)	43.3	0.3	1.8	9.4	54.4
PCB 180	117 (33.8%)	42 (12.1%)	46.1	1.7	7.5	28.8	122.0

[a]UDL: 20ng/g dust

[b]MPQL: 63.4ng/g dust (PCB 105), 56.3ng/g dust (PCBs 138, 153, 170, 180)

[c]Based on a single imputation previously defined[2,25]

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Table 2
Determinants of PCB levels in carpet dust: Detroit metropolitan area (n=204), 1998-2000

PCB congener	Odds Ratio (90% CI)	p-value
Total PCB (low/medium/high)[a]		
% developed land ≤ 2km	1.02 (1.01-1.04)	0.02
Total number of industrial facilities ≤ 2km	0.88 (0.78-0.98)	0.05
Number of rooms[b]	0.72 (0.59-0.88)	<0.01
Education		
<12yrs	1.00	
12-15yrs	4.09 (1.36-12.33)	0.04
16+yrs	4.12 (1.24-13.62)	0.05
PCB 138 (>MPQL/≥MPQL)		
Number of publishing/printing facilities[c]	0.37 (0.17-0.77)	0.03
Distance to freight route (m)		
0-284	1.00	
284-755	2.22 (1.03-4.80)	0.09
>755	0.89 (0.36-2.24)	0.84
Number of rooms[b]	0.62 (0.49-0.78)	<0.01
Education		
<12yrs	1.00	
12-15yrs	5.97 (1.63-23.24)	0.03
16+yrs	10.87 (2.57-45.94)	<0.01
PCB 153 (<MPQL/≥MPQL)		
% developed land ≤ 2km	1.03 (1.01-1.05)	0.01
Number of publishing/printing facilities[c]	0.42 (0.20-0.88)	0.05
Number of misc. manufacturing facilities[d]	3.83 (1.26-11.60)	0.05
Distance to railroad (m)		
0-1419	1.00	
1419-3774	2.29 (1.11-4.70)	0.06
>3774	1.66 (0.72-3.83)	0.32
Number of rooms[b]	0.78 (0.64-0.96)	0.05
PCB 180 (<MPQL/≥MPQL)		
% developed land ≤ 2km	1.04 (1.02-1.07)	<0.01
PCB exposed job[e]	7.18 (1.21-42.72)	0.07

[a] Low = no congener detected above maximum practical quantitation limit (MPQL), Medium = any congener detected above MPQL and below median measured concentration, High = any congener detected above median measured concentration)

[b] number of rooms with carpet that were usually vacuumed with the sampled vacuum cleaner: semi-continuous variable: 1-5 and 6+

[c] SIC 27: periodicals (publishing/printing)

[d]SIC 39: misc. manufacturing industries

[e]>50% chance of PCB exposure, jobs include electricians, electrical and electronic equipment repairers and technicians

Table 3

Determinants of PCB levels in carpet dust: Iowa (n=342), 1998-2000

PCB congener	Odds Ratio (90% CI)	p-value
Total PCB (low/medium/high)[a]		
% developed land ≤ 2km	1.01 (1.00-1.02)	0.05
Distance to railroad (m)		
0-1419	1.00	
1419-3774	2.20 (1.23-3.94)	0.03
>3774	1.48 (0.73-2.98)	0.36
Housing type		
single family	1.00	
Other	0.18 (0.03-0.95)	0.09
Education		
<12yrs	1.00	
12-15yrs	0.45 (0.21-1.00)	0.10
16+yrs	0.96 (0.40-2.29)	0.93
PCB 138 (<MPQL/≥MPQL)		
% developed land ≤ 2km	1.01 (1.00-1.03)	0.07
Distance to railroad (m)		
0-1419	1.00	
1419-3774	2.60 (1.32-5.12)	0.02
>3774	1.18 (0.48-2.89)	0.76
Oriental rugs (yes/no)	2.85 (1.18-6.88)	0.05
Education		
<12yrs	1.00	
12-15yrs	0.33 (0.14-0.77)	0.03
16+yrs	0.67 (0.25-1.78)	0.50
PCB 153 (<MPQL/≥MPQL)		
% developed land ≤ 2km	1.02 (1.00-1.03)	0.04
Distance to railroad (m)		
0-1419	1.00	
1419-3774	2.81 (1.49-5.28)	<0.01
>3774	1.86 (0.84-4.08)	0.20
PCB 180 (<MPQL/≥MPQL)		
Number of industrial machinery/equipment facilities[b]	1.93 (1.06-3.51)	0.07
Distance to railroad (m)		
0-1419	1.00	
1419-3774	4.00 (1.74-9.17)	<0.01
>3774	1.29 (0.46-3.58)	0.69

[a] Low = no congener detected above maximum practical quantitation limit (MPQL), Medium = any congener detected above MPQL and below median measured concentration, High = any congener detected above median measured concentration)

[b] SIC 35: industrial machinery and equipment

Table 4
Determinants of PCB levels in carpet dust: Los Angeles County (n=295), 1998-2000

PCB congener	Odds Ratio (90% CI)	p-value
Total PCB (low/medium/high) [a]		
% developed land ≤ 2km	1.04 (1.01-1.06)	0.02
Number of industrial facilities (multiple SIC)[b]	0.92 (0.88-0.97)	<0.01
Distance to street (m)		
0-546	1.00	
546-1000	0.44 (0.16-1.20)	0.18
>1000	0.21 (0.09-0.53)	<0.01
PCB exposed job[c]	6.73 (1.27-35.79)	0.06
PCB 138 (>MPQL/≥MPQL)		
% developed land ≤ 2km	1.05 (1.01-1.10)	0.04
Number of chemical wholesaler facilities[d]	0.27 (0.12-0.65)	0.01
Distance to major road (m)		
0-546	1.00	
546-1000	0.80 (0.28-2.35)	0.74
>1000	0.18 (0.06-0.58)	0.02
PCB 153 (<MPQL/≥MPQL)		
% developed land ≤ 2km	1.05 (1.01-1.09)	0.06
Number of chemical wholesaler facilities[d]	0.50 (0.28-0.89)	0.05
Distance to major road (m)		
0-546	1.00	
546-1000	0.54 (0.17-1.71)	0.38
>1000	0.22 (0.08-0.62)	0.02
PCB exposed job[c]	6.99 (1.20-40.83)	0.07
PCB 180 (<MPQL/≥MPQL)		
% developed land ≤ 2km	1.11 (1.02-1.20)	0.05
Number of furniture and fabricated metal product facilities[e]	0.72 (0.58-0.88)	0.01
Number of dioxin facilities ≤ 5km	4.34 (1.39-13.60)	0.03
Distance to major road (m)		
0-546	1.00	
546-1000	0.15 (0.02-0.94)	0.09
>1000	0.16 (0.04-0.60)	0.02

[a]Low = no congener detected above maximum practical quantitation limit (MPQL), Medium = any congener detected above MPQL and below median measured concentration, High = any congener detected above median measured concentration)

[b]food and kindred products (SIC 20), furniture (SIC 25), stone, clay and glass products (SIC 32), primary metal industries (SIC 33), fabricated metal products)SIC 34), chemical wholesalers (SIC 50)

[c]>50% chance of PCB exposure, jobs include electricians, electrical and electronic equipment repairers and technicians

[d]SIC 50: chemical wholesalers

[e]furniture (SIC 25),fabricated metal products (SIC 34)

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Table 5

Determinants of PCB levels in carpet dust: Seattle metropolitan area (n=346), 1998-2000

PCB congener	Odds Ratio (90% CI)	p-value
Total PCB (low/medium/high) [a]		
Block group population (1,000/mi^2)	1.08 (1.01-1.14)	0.04
Number of food/kindred products and electronic/other electric equipment facilities[b]	1.22 (1.04-1.43)	0.05
Number of industrial machinery/equipment facilities[c]	2.13 (1.33-3.41)	<0.01
Median housing age[d]		
<1940	1.00	
1940-1979	0.67 (0.31-1.44)	0.38
1980+	0.21 (0.08-0.55)	<0.01
PCB 138 (<MPQL/≥MPQL)		
Block group population (1,000/mi^2)	1.14 (1.07-1.22)	<0.01
Number of industrial machinery/equipment facilities[c]	2.38 (1.41-4.01)	<0.01
Median housing age[d]		
<1940	1.00	
1940-1979	0.96 (0.40-2.32)	0.94
1980+	0.23 (0.07-0.70)	0.03
PCB 153 (<MPQL/≥MPQL)		
Block group population (1,000/mi^2)	1.12 (1.05-1.19)	<0.01
Number of industrial machinery/equipment facilities[c]	1.94 (1.21-3.12)	0.02
Median housing age[d]		
<1940	1.00	
1940-1979	0.82 (0.36-1.85)	0.69
1980+	0.21 (0.08-0.58)	0.01
PCB 180 (<MPQL/≥MPQL)		
Number of industrial machinery/equipment facilities[c]	2.10 (1.16-3.82)	0.04
Median housing age[d]		
<1940	1.00	
1940-1979	0.39 (0.16-0.93)	0.07
1980+	0.07 (0.02-0.24)	<0.01

[a] Low = no congener detected above maximum practical quantitation limit (MPQL), Medium = any congener detected above MPQL and below median measured concentration, High = any congener detected above median measured concentration)

[b] food and kindred products (SIC 20), electronic and other electric equipment (SIC 36)

[c] SIC 35: industrial machinery and equipment

[d] median year of construction of housing structures at the census block group level

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