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Pyrethroid levels in toddlers' breathing zone following a simulated indoor pesticide spray

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Abstract

Application of pyrethroid insecticides in residential settings may result in children's exposures to these chemicals and possible adverse health effects. Household dust is a recognized reservoir for pyrethroids and a potential medium for multi-route pyrethroid exposure. Young children move and play in a manner that resuspends dust, and since their breathing zone is close to the floor, they will have higher inhalation exposure to pesticide-laden dust than other age groups. Directly measuring a toddler's exposure to household dust presents many logistic challenges. We simulated the dust resuspension induced by a toddler using a robot, which also served as a platform to collect air samples at the toddler's breathing zone height. We performed simulated pyrethroid residential spray and dust resuspension experiments on vinyl and carpeted floors. The mean pyrethroid airborne concentrations in the stationary and mobile samples were 0.065 $\mu\text{g}/\text{m}^3$ and 0.143 $\mu\text{g}/\text{m}^3$ for the vinyl floor with 1 g/m^2 dust loading, and 0.034 $\mu\text{g}/\text{m}^3$ and 0.061 $\mu\text{g}/\text{m}^3$ for the carpeted floor with 10 g/m^2 dust loading, respectively. Pyrethroids concentrations in the settled dust samples were significantly lower than that measured in the stationary and mobile samples in the carpeted floor experiments. Thus, the use of stationary samples and settled dust samples may underestimate a toddler's personal inhalation exposure to pyrethroids in residential houses.

Keywords

Pyrethroids; Toddlers; Resuspended dust; Inhalation exposure

Introduction

The widespread use of pyrethroids in residential houses [1, 2] and the increasing concern about the pyrethroids' adverse health effects on children [3, 4] have led to several studies investigating multiple exposure pathways and routes of children's exposure to pyrethroids [5–12]. Residential pesticide use represents an important source of children's exposure to

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pyrethroid insecticides [5, 10]. Pyrethroids applied in indoor environments redistribute from their initial locations to all indoor surfaces [13], especially to house dust because they are semi-volatile organic compounds with high partition coefficients between the solid phase and gas phase (log K_{oa} around 10) (EPISuite™, <https://www.epa.gov/tsca-screening-tools/epi-suite-estimation-program-interface>). Thus, house dust is a major reservoir for pyrethroids in homes [7].

Children are more vulnerable to pyrethroid exposure than adults due to their developing physiology and their vigorous indoor activities. Physiologically, children are at an early stage of physical development, and kinetics of toxins (including absorption, distribution, metabolism, and elimination of a chemical) differ between children and adults. Children's developing organs are particularly susceptible to toxic insult because cell division occurs at a higher rate compared to adults, and some functional excretion systems are still immature [14]. Compared with adults, children have greater metabolic rates and activity levels, which lead to a greater breathing rate on a per-body-weight basis [15]. Physically, children's behaviors and their interactions with their environment can increase their exposure to environmental contaminants, particularly indoors where they spend approximately 90% of their time [16]. Their vigorous activities such as playing on the floor can resuspend dust, leading to an increased indoor particle concentration in their breathing zone. Children's higher breathing rates per-body weight then lead to potentially increased inhalation exposure, especially since their breathing zone is closer to the floor, where resuspended particle concentrations are higher when compared to the breathing zone height of adults [17]. In addition to pyrethroid exposure due to inhalation of resuspended dust, infants' and toddlers' mouthing behaviors also result in ingestion exposure to dust contaminated with pyrethroids [18, 19]. Though inhalation is estimated to contribute <1% of the total pyrethroid exposure to children [20], evidence in the literature suggests that pyrethroid inhalation exposure could adversely impact a child's respiratory system [21].

Toddlers, who are one to three years old and at the early stages of walking, potentially are in the most vulnerable children's age group when it comes to pyrethroid exposure. However, collecting personal air samples for this age group is difficult due to the size and weight of the sampling equipment and toddlers' propensity for putting objects in their mouths. Characterization of children's inhalation exposure typically relies on stationary air sampling or settled dust measurements [22–25]. Stationary air sampling is likely to underestimate children's inhalation exposure because it underestimates concentrations of airborne dust caused by children's indoor activities. The underestimation of particulate matter exposure is likely greater for young children because the commonly used height for stationary samplers of 110 cm [26] is higher than a toddler's average breathing zone height [27]. Previous studies have used the concentration of semi-volatile organic compounds in the settled dust to estimate concentrations of these contaminants in the air [28–30]. However, the particle size distribution in the resuspended dust and settled dust might be different which potentially results in different contaminant concentrations. This difference is especially important because the smaller size fraction of resuspended dust is expected to be enriched in semi-volatile organic compounds compared to settled dust due to a greater surface area to volume ratio in smaller particles [31, 32].

Given the uncertainties in estimating children's exposures to dust in general and to pyrethroids in particular, the overall objectives of this study are to compare different approaches for collecting airborne and surface-borne dust when estimating pyrethroid concentrations in toddlers' breathing zones and to provide a better understanding and characterization of toddlers' inhalation exposures to pyrethroids in homes. We used a robotic surrogate to simulate toddlers' indoor activities and mounted a personal sampler on the robotic surrogate to collect mobile air samples that represented children's exposure. Stationary air samples and settled dust samples were collected concurrently. Pyrethroid concentrations as well as particle mass concentrations were analyzed and compared among mobile air, stationary air and settled dust samples.

Methods

Description of experiment room

The study was conducted in an empty office in the Robert Wood Johnson Medical School in Piscataway, NJ. The room dimensions were 3.6 m (length) $\times$ 3.3 m (width) $\times$ 3.5 m (height), yielding a floor area of 11.9 m² and a volume of 41.6 m³.

Surrogate toddler—Robotic ReCon Rover

A commercially available robot, ReCon 6.0 Programmable Rover from SmartLab Toys (<https://smartlabtoys.com/products/recon-6-0-programmable-rover>, Bellevue, WA, USA) (Fig. 1), was used to simulate a toddler's indoor movements and carry sampling equipment. It is powered by three C-type batteries and can be programmed through an LCD screen and 10-button keypad to control its movements in a sequence of directions: forward, backward, 45 and 90 degree turns. The rover weighs 1.5 kg and has dimensions of 23 $\times$ 20 $\times$ 28 cm. When equipped with sampling devices (a PM₁₀ sampler, a sampling pump, and an optical particle counter), it weighs around 3 kg. We programmed the ReCon Rover to go in a spiral pattern in the room to cover the entire room area at its own fixed speed of 8 cm/s. The researcher stayed in the experimental room to restart and redirect the robot if it encountered a wall.

Flooring types

Two flooring types, a vinyl floor (Traffic MASTER black and white decorative paver vinyl sheet, Model #U9430.271K509G144) and a medium pile carpet (Hot Shot II - Color Tuscan Texture carpet, Model # H2004-402-1200-AB) were used in this study. After installation, the carpet was vacuumed using a Scorpion Quick Flip handheld vacuum cleaner (Model 08220, Dirt Devil, Glenwillow, OH, USA) until no large fibers were visible in a dust collector after vacuuming an area of 60 cm $\times$ 60 cm (approximately 5 min collection time).

Between tests on the vinyl floor, a broom was used to remove the bulk of the floor dust, and a mop wetted with an ethanol and water mixture (volume ratio of 1:30) was used to mop the floor three times. A towel wetted with an ethanol and water mixture (volume ratio of 1:2) was used to clean the walls and other interior surfaces. After cleaning, the room was left for 1–2 days to equilibrate. For each carpet test, the old carpet was removed from the room, and a new piece of carpet was used.

Simulated dust loading

House dust was obtained from vacuum cleaners from 16 residential houses in New Jersey, USA. The dust was initially sieved through a 125 μm mesh to remove very large particles and fibers as they would not contribute to the resuspended dust particles, which are primarily $<10 \mu\text{m}$ [33]. A 200 mg portion of dust from each house was analyzed for pyrethroid levels as described later in the sample analysis section. Dust samples with pyrethroid levels below the detection limit of 10 ng/g were selected for background dust: these samples were homogenized and stored at -4°C in a freezer for subsequent use. The average dust loading and the extent of dust resuspension varies with flooring types, with carpets reported to have higher dust loadings than hard floor surfaces [22]. A vinyl floor dust loading of 1 g/m^2 and a carpet dust loading of 10 g/m^2 were selected to be within the ranges reported in U.S. homes [23, 24] and to provide sufficient resuspended dust to be measured. The total amount of applied dust (g) was calculated as the floor area (m^2) multiplied by the target dust loading (g/m^2), and was 12 g for the vinyl floor and 120 g for the carpeted floor.

The dust was loaded onto the floor using a dust dispenser: a 25 mL Pyrex midjet impinger (Corning Inc., Corning, NY, USA) with an inlet connected to an air pump (positive pressure) providing an air flow of 25 L/min through the impinger. The dust was put at the bottom of the impinger, and the air was forced through the inlet nozzle, which resulted in the dust being suspended within the impinger and released through the outlet nozzle.

The room was divided into four sections for the vinyl floor and eight sections for the carpeted floor. The dust was sprayed using the impinger while slowly walking across each section to deposit the dust evenly across the entire room. The impinger was periodically tapped with a stainless steel laboratory spatula to prevent the dust from clogging the nozzle. After the dust was sprayed, the room was left undisturbed overnight to allow the dust to settle.

After spraying the carpet, the settled dust was embedded into the carpet to be representative of in-use carpets [34]. Briefly, a carpet roller (Model 10–935, Roberts Consolidated Industries, Inc. Boca Raton, FL, USA) was used as a dust embedment tool. The roller was pulled in both directions with the handle held at an angle of 30–45 degrees to the floor. The dust embedment tool was rolled over the entire carpeted area for exactly 30 strokes (a movement in one direction covering the length of the flooring is one “stroke”). The applicator walked at a uniform speed of approximately 0.5 m/s. After the dust embedment had been completed, the room was left for at least one day to allow any resuspended dust to settle and to allow the temperature and relative humidity in the room to equilibrate.

In order to evaluate the floor dust loading distribution, sixteen pieces of weighing paper were placed on the vinyl floor prior to spraying the dust and left overnight while the dust settled. The weighing papers were collected, and the weight of the dust was measured using a Mettler Toledo AT261 balance (Mettler-Toledo GmbH, Laboratory & Weighing Technologies, Greifensee, Switzerland). The dust loading on each section was calculated and compared with the expected value (data presented in the supplemental material).

Indoor pyrethroid application

A 0.5% emulsion permethrin spray solution was prepared by diluting a permethrin concentrate purchased from Control Solutions, Inc. (Lot#: 20184, Pasadena, TX, USA). A commercially available polyethylene sprayer (Model 2121 from Chapin International, Inc. Batavia, NY, USA) was used to spray pyrethroids in the room. Permethrin was sprayed along the baseboards of the room after the background PM₁₀ and settled dust samples were collected. The sprayer nozzle was held approximately 30 cm from the floor, and the applicator moved at a walking speed of 0.5 m/s. The spray resulted in a slightly visible film on the floor. The permethrin spray protocol was intended to simulate residential baseboard spraying practices for pest control.

Sample collection

Airborne samples (mobile samples and stationary samples, Fig. 2) and settled dust samples were collected prior to the permethrin application (background samples), then at one day and three days after the permethrin application. Airborne samples were collected on a 37 mm Teflon filter with 2.0 µm pore size from Pall Life Sciences (Port Washington, NY, USA) installed in a Personal Environmental Monitor (PEM) (10-µm cut-point at 10 L/min, SKC Inc., Eighty Four, PA, USA). The PEM samplers were connected to pumps with Tygon tubing and placed at a height of 80 cm. This height represents a toddler's breathing zone following WHO Child Growth Standards, which reports average heights for toddlers of 1–3 years of age in a range of 74–95 cm [35]. We used a Model 400 Micro-Environmental Monitor (MEM™) (MSP Corporation, Shoreview, MN, USA) and an SKC Leland Legacy pump to provide 10 L/min flow rate for the stationary and mobile samplers, respectively. The pump flow rates were checked before and after sampling using a DryCal® DC-Lite primary flow meter (MesaLabs, Butler, NJ, USA). One stationary sample and one mobile sample were collected on each sampling day. Sampling duration was 4 h for the vinyl floor experiments and 8 h for the carpeted floor experiments. The sampling time was extended for the carpeted floor to improve the detection limit of permethrin.

In addition to airborne samples, settled dust samples were collected. For the vinyl floor experiments, settled dust samples were collected using pre-weighed PreSep, Drain Disc. 50 × 55 mm wipe filters (GE Water & Technologies, Feasterville-Trevose, PA, USA). The surface was wiped with 3 successive filters for each sample using water as a filter wetting solvent. Each day, one 23 × 23 cm center sample and one 23 × 23 cm corner sample from one side of the room were collected. For the carpeted floor experiments, settled dust samples were collected by mounting a DustChek™ (EM lab P&K, Marlton, NJ, USA) to the hose of a Scorpion Quick Flip Handheld Vacuum (Model 8220, Dirt Devil, Glenwillow, OH, USA). DustChek™ is a plastic dust collector that is attached to the vacuum cleaner hose to collect dust samples. Each day, one 5-minute center sample was collected from a 60 × 60 cm area, and one 6-minute composite corner sample was collected from three sides of the room, each with an area of 45 × 45 cm.

Sample preparation and analysis

All 37 mm Teflon filters were equilibrated for a minimum of 72 h prior to weighing in a weighing room with a narrow range of temperature (22–24 °C) and relative humidity (30–

40%). Filters were weighed using a Mettler Toledo MT5 Microbalance (Columbus, OH, USA) and placed in individual containers until they were loaded into the samplers. After sample collection, the filters were returned to the same weighing room to equilibrate at the same temperature and humidity for a minimum of 72 h prior to reweighing with the same microbalance [36]. PM₁₀ concentrations were calculated as the amount of collected particles divided by the volume of sampled air.

After the filters were weighed, pyrethroids from filter samples were extracted using 6 mL of a 1:1 hexane: acetone solution while being sonicated for 10 min. The extract was then centrifuged at 4000 rpm for 5 min and the supernatant transferred to a clean test tube. The volume was reduced using a Meyer N-Evap analytical nitrogen evaporator (Organomation, Berlin, MA, USA) to approximately 0.3–0.5 mL. The extract was then transferred to glass inserts that fit into GC vials and evaporated to dryness. Lastly, the extract was reconstituted in 100 µL of hexane.

A 1 µL aliquot of the sample extract was analyzed by Gas Chromatography-Electron Capture Detector (HP 5890 Series II equipped with an HP 7673 auto-sampler and a DB1701 column (30 m × 0.25 mm × 0.25 µm)). The injector was operated at a temperature of 250 °C, in the splitless injection mode. Helium was used as the carrier gas at a constant flow of 1.4 mL/min. The initial column temperature of 140 °C was held for 2 min, then raised to 230 °C at a rate of 10 °C per minute, held for 2 min, and finally raised to 250 °C at a rate of 8 °C per minute, where it was held for 10 min. The Electron Capture Detector was maintained at 300 °C.

Statistical analysis

In total, three sets of vinyl floor experiments and five sets of carpeted floor experiments were conducted. Comparison of permethrin airborne PM₁₀ concentrations (µg/m³) measured in stationary to the mobile samples was performed using a two-tailed paired t-test with statistical difference of $p < 0.05$. Comparison of permethrin dust concentration (µg/g) in mobile, stationary and settled dust samples was performed using a one-way ANOVA test, and a post-hoc Tukey's HSD test applied to identify which pair (s) of samples had statistical differences of $p < 0.05$.

Results

PM₁₀ concentrations in air samples

Nine pairs of mobile and stationary airborne samples were collected in the vinyl floor experiments, while fifteen pairs of mobile and stationary airborne samples were collected in the carpeted floor experiments. The mean and standard deviation of the PM₁₀ concentrations in the stationary and mobile samples measured for the vinyl floor and carpeted floor experiments are presented in Table 1. The overall observed means of the PM₁₀ concentrations collected from stationary samples were 17.1 µg/m³ and 27.0 µg/m³ for the vinyl floor and carpeted floor experiments, respectively. The means of the PM₁₀ concentrations measured in mobile samples were 38.4 µg/m³ and 40.4 µg/m³ for the vinyl floor and carpeted floor experiments, respectively.

Paired *t*-test results between PM₁₀ concentrations in mobile and stationary samples showed that mobile PM₁₀ concentrations were statistically significantly higher than stationary PM₁₀ concentrations for both vinyl floor and carpeted floor experiments with $p < 0.001$. This finding supports the notion that stationary sampling underestimates toddlers' inhalation exposure to resuspended particles.

Permethrin dust concentrations in airborne and settled dust samples (µg/g)

Permethrin dust concentrations in mobile, stationary and settled dust samples measured in the vinyl floor and carpeted floor experiments are presented in Fig.3. For the carpeted floor, permethrin dust concentrations (mean $\pm$ standard deviation) were 2080 ± 1030 µg/g and 1550 ± 700 µg/g for the mobile and stationary samples, respectively. The permethrin dust concentration in the settled dust was 400 ± 240 µg/g, which was approximately 20 and 25% of that measured in mobile and stationary samples, respectively. The permethrin concentration in the settled dust was statistically different from the stationary and mobile samples based on a post-hoc Tukey HSD test with $p < 0.05$. For the vinyl floor, the highest permethrin dust concentrations were found in settled dust samples with a mean $\pm$ standard deviation of 6430 ± 5630 µg/g, while permethrin dust concentrations in mobile and stationary samples were 4210 ± 1630 µg/g and 4750 ± 2930 µg/g, respectively. None of the permethrin concentrations were statistically different based on the ANOVA test.

Airborne permethrin concentrations (µg/m³)

Airborne permethrin concentrations in stationary samples and mobile samples measured in the vinyl floor and carpeted floor are presented in Table 2. The mean permethrin airborne concentrations measured in the vinyl floor experiments were 65 ± 26 ng/m³ and 143 ± 51 ng/m³ for stationary and mobile samples, respectively. The mean permethrin airborne concentrations in the carpeted floor experiments were lower than that in the vinyl floor measurements, being 34 ± 20 ng/m³ and 61 ± 30 ng/m³ for stationary and mobile samples, respectively. Paired *t*-tests between permethrin airborne concentrations in mobile and stationary samples showed that mobile permethrin airborne concentrations were significantly higher than stationary permethrin concentrations in both vinyl floor and carpeted floor experiments at a significance level of 0.05, suggesting that stationary measurements of airborne pyrethroid concentrations potentially underestimate toddlers' inhalation exposures to pyrethroids by approximately a factor of two.

Discussion

Comparison of particle mass concentrations in airborne samples

There is limited PM exposure data for children in the age group of 1–3 years. Shalat et al. [36]. applied a robotic personal sampling platform (PIPER: Pre-Toddler Inhalable Particulate Environmental Robot) to measure inhalable PM concentrations in a toddler's breathing zone in residential homes with carpeted and bare floors. PIPER was programmed to change both the speed of movement and the vertical sampling height to simulate a toddler's movement according to his/her age and gender. Based on measurements in 55 homes, the authors reported arithmetic means of 30.7 µg/m³ and 34.6 µg/m³ for stationary and mobile inhalable particle (<100 µm) concentrations measured in homes with bare floors,

while arithmetic means of $41.5 \mu\text{g}/\text{m}^3$, and $95.6 \mu\text{g}/\text{m}^3$ were reported for stationary and mobile inhalable PM concentrations in homes with carpeted floors, respectively. Sagona et al. [37]. measured inhalable PM concentrations in 2-year-old children's breathing zones via a lightweight personal sampler in residential homes to evaluate personal PM exposures. They reported an average inhalable PM concentration of $331 \mu\text{g}/\text{m}^3$. The PM concentrations measured in our study were lower than those presented in the Shalat and Sagona studies. The major reason for our lower observed PM values is we measured PM_{10} ($d < 10 \mu\text{m}$) and not inhalable particles ($d < 100 \mu\text{m}$). An additional contributor could be the differences in the dust loadings of the floors [38].

The particle mass concentrations measured in mobile samples were similar for both vinyl and carpeted floor experiments, with mean concentrations of $38.4 \mu\text{g}/\text{m}^3$ and $40.4 \mu\text{g}/\text{m}^3$, respectively. However, the particle mass concentrations measured in stationary samples in the carpeted floor experiments ($27.0 \mu\text{g}/\text{m}^3$) were higher than those measured in the vinyl floor experiments ($17.1 \mu\text{g}/\text{m}^3$). Differences in air concentrations might have resulted from the differences in dust loadings in two flooring experiments. However, we do not know why only the stationary but not the mobile samples had different air concentrations for PM_{10} .

Comparison of permethrin dust concentrations

A significant difference was found between the airborne and settled dust permethrin concentrations for the carpeted floor experiments, but not for the vinyl floor experiments, which indicates there might be two different release scenarios occurring depending on flooring type. For the carpeted floor experiments, the difference in particle size distributions between settled dust and resuspended dust might cause the measured differences in permethrin dust concentrations on the settled dust and resuspended dust. Lewis et al. [31]. measured pesticide concentrations in different size fractions of residential house dust and reported that the pesticide dust concentrations increased with decreasing particle sizes. Cao et al. [32]. reviewed several studies on the distribution of toxic chemicals according to particle size in settled dust and concluded that concentrations of toxic chemicals increased with decreasing particle sizes. In our study, the greater surface area to mass ratio of PM_{10} fraction of the resuspended dust compared to the sieved settled dust particles with a diameter $< 125 \mu\text{m}$ could be expected to result in a greater permethrin concentration in the resuspended dust since it is comprised of smaller particles. While the permethrin concentrations in stationary and mobile samples were statistically higher than the permethrin concentrations in the settled dust for carpet experiments, no difference was found for the vinyl floor experiments. One possible explanation for the permethrin levels being the same in the settled dust, stationary and mobile samples for the vinyl floor experiments is that the wipe samples used to collect the settled dust also collect permethrin adhering to the flooring material (permethrin that would not be resuspended) and not just dust particles that would be resuspended. To evaluate this possibility, one set of experiments was performed on the vinyl floor with one wipe sample and one vacuum sample (no beater bar used) collected to evaluate the difference in permethrin dust concentrations between the wipe sample and the vacuum sample. Comparable permethrin concentrations were found in the wipe sample ($5420 \mu\text{g}/\text{g}$) and the vacuum sample ($5560 \mu\text{g}/\text{g}$), which indicated that the wipe sample was collecting predominately dust and not pesticide residue from the vinyl sheet (no statistical

test was used). Future investigations are needed to evaluate why the expected differences were not observed among the stationary, mobile and settled dust samples for the vinyl floor experiments.

Average permethrin dust concentrations ($\mu\text{g/g}$) were compared using unpaired t-tests between the vinyl floor and carpeted floor experiments. Significant differences were found between permethrin concentrations measured in the vinyl and carpeted floors across the three different sampling methods, with concentrations from vinyl floor experiments being higher. T-test p-values for mobile, stationary and settled dust comparisons on vinyl and carpeted floors were 0.0061, 0.0046 and 0.0038, respectively. There are several possible explanations for the differences. In our experiments, the carpet had a ten-fold higher dust loading (10 g/m^2) compared to the vinyl floor (1 g/m^2). Since the same amount of pesticide was applied to both floor types, the permethrin dust concentration is expected to be higher for the vinyl floor experiments. On average, a 15-fold higher permethrin concentration ($\mu\text{g/g}$) was found in vinyl floor dust samples compared to the carpeted floor samples. A second difference is that the carpet has a larger surface area to adsorb permethrin than the vinyl floor, which may have resulted in a portion of the permethrin being absorbed by carpet fiber rather than the dust. This would further reduce the permethrin concentrations in the resuspended dust and settled dust from the carpet. The vinyl floor has a flat surface and, therefore, lowers adsorption capacity, which may have resulted in higher permethrin concentrations in the dust.

Comparison of permethrin airborne concentrations

Airborne pyrethroid concentrations measured in our study were consistent with airborne concentrations measured in homes following a pesticide application. Berger-Preiß et al. [39]. applied three different formulations of pyrethroids including permethrin in a model house with carpeted floor to simulate an indoor pest control. They found that the permethrin concentration in resuspended particles was approximately $40 \mu\text{g/m}^3$ immediately after application. The measured stationary permethrin concentrations are comparable to those in our study, which were $65 \pm 26 \mu\text{g/m}^3$ and $34 \pm 20 \mu\text{g/m}^3$ (mean $\pm$ standard deviation) for the vinyl and carpeted floor stationary samples, respectively. Further, in our study, paired t-tests showed that there were statistically significant differences between stationary and mobile permethrin airborne concentrations for both vinyl and carpeted floors, with stationary permethrin airborne concentrations being lower. The results indicated that stationary samples underestimated airborne permethrin concentrations compared to mobile samples.

Some limitations of our study are worth noting. The robot used in our study was not programmed to closely match toddlers' indoor activities as it moved at a constant speed in a pre-set pattern rather than using different activity profiles that a toddler may engage in. This could have affected the amount of dust resuspended and the simulated breathing zone height. In addition, our study was performed in a simulated home environment instead of an actual residential house.

Our study results indicate that stationary samples and settled dust samples likely underestimate young children's exposures to SVOCs associated with resuspended dust.

Conclusion

The airborne permethrin concentrations collected in the mobile samples were twice as high as those measured in the stationary samples for both vinyl and carpeted floor experiments, and permethrin dust concentrations in the resuspended dust collected by the mobile robot samples were four-fold higher than those in the settled dust samples for the carpeted floor experiments. The results indicate that using stationary and settled dust samples may underestimate toddlers' inhalation exposures to pyrethroids.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1.
RecCon Rover and samplers

Fig. 2.
Sampling location

Fig. 3. Boxplot of permethrin dust concentrations ($\mu\text{g/g}$) in stationary, mobile and settled dust samples for the vinyl floor and carpeted floor experiments (*: Statistically different at $p < 0.05$)

Table 1

PM₁₀ concentrations in stationary and mobile airborne samples (µg/m³)

	Mean ± standard deviation	Paired t-test
Vinyl floor (dust loading: 1 g/m ²)	Stationary 17.1 ± 7.1 Mobile 38.4 ± 10.4	N = 9, p-value = 0.001
Carpeted floor (dust loading: 10 g/m ²)	Stationary 27.0 ± 10.4 Mobile 40.4 ± 19.7	N = 15, p-value = 0.001

Table 2

Airborne permethrin concentrations (ng/m³)

		Mean ± Standard deviation	Paired <i>t</i> -test
Vinyl floor	Stationary	65 ± 26	<i>N</i> = 6, <i>p</i> -value = 0.029
	Mobile	143 ± 51	
Carpeted floor	Stationary	34 ± 20	<i>N</i> = 10, <i>p</i> -value = 0.002
	Mobile	61 ± 30	