Environmental Research 222 (2023) 115412

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Do cats mirror their owner? Paired exposure assessment using silicone bands to measure residential PAH exposure

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ARTICLE INFO

Keywords:
Domestic animal
Sentinel specie
Residential exposure
Polycyclic aromatic hydrocarbons
Wristband
Wearable sampler

ABSTRACT

It has been suggested that domestic animals can serve as sentinels for human exposures. In this study our objectives were to demonstrate that i) silicone collars can be used to measure environmental exposures of (domestic) animals, and that ii) domestic animals can be used as sentinels for human residential exposure. For this, we simultaneously measured polycyclic aromatic hydrocarbons (PAHs) using silicone bands worn by 30 pet cats (collar) and their owner (wristband). Collars and wristbands were worn for 7 days and analyzed via targeted Gas Chromatography-Mass Spectrometry (GC-MS). Demographics and daily routines were collected for humans and cats. Out of 16 PAHs, 9 were frequently detected (>50% of samples) in both wristbands and collars, of which Phenanthrene and Fluorene were detected in all samples. Concentrations of wristbands and collars were moderately correlated for these 9 PAHs (Median Spearman's r = 0.51 (range 0.16–0.68)). Determinants of PAH concentrations of cats and humans showed considerable overlap, with vacuum cleaning resulting in higher exposures and frequent changing of bed sheets in lower exposures. This study adds proof-of-principle data for the use of silicone collars to measure (domestic) animal exposure and shows that cats can be used as sentinels for human residential exposure.

1. Introduction

Exposure to environmental chemicals can be detrimental to both animal and human health. For example, air pollution has been linked to increased mortality both in humans as in cattle (Egberts et al., 2019). Environmental tobacco smoke exposure has been linked to lung cancer in both human and animal populations (Reif et al., 1992). The use of pesticides, in particular 2,4-dichlorophenoxyacetic acid, has been associated to malignant lymphoma in both dogs and humans (Hayes et al., 1991).

Polycyclic aromatic hydrocarbons (PAHs) describe an omnipresent group of chemicals that is hazardous to health (Sun et al., 2021). PAHs consist of two or more benzene rings and are primarily formed during the incomplete combustion of organic compounds such as coal, petrol, wood and oil (Hassanvand et al., 2015). Cooking and heating with solid fuels are considered the main sources in developing countries, while traffic emission and industrial processes are primary contributors in developed areas (WHO 2016; Hoseini et al., 2018). Exposure to these organic compounds has been linked to cancer development (Boström et al., 2002), impairment of reproduction (Kumar et al., 2021) and cardiotoxicity (McGee et al., 2013), among other adverse health effects. Because of the overlap in disease risk exposure assessment in humans and animals, domestic animals have been suggested as sentinels for human exposure (Reif, 2011; Henríquez-Hernández et al., 2017).

Exposure assessment often requires active sampling devices (ASDs) and/or biomonitoring (e.g. urine, blood). However, regarding ASDs, despite their accuracy and precision, this are often noisy, expensive, require a trained operator to function (Bohlin et al., 2007) and we hypothesize that they might not be well tolerated by animals. Biological monitoring, which is usually a preferred method for assessing integrated

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https://doi.org/10.1016/j.envres.2023.115412
Received 20 December 2022; Received in revised form 27 January 2023; Accepted 31 January 2023
Available online 1 February 2023

exposure, mainly reflects short-term exposures. Furthermore, for some matrixes, such as blood, collection is more invasive (Oerlemans et al., 2021). Passive sampling devices (PSDs) provide a possible alternative due to their non-invasive nature, while suited to measure long-time exposure in residential environments (Dixon et al., 2018). Silicone wristbands have been developed as PSDs (O'Connell et al., 2014). Like other PSDs, silicone wristbands adsorb organic compounds on their silicone matrices until they reach equilibrium (Anderson et al., 2017; Tromp et al., 2019). Thus far, wristbands have been used to capture PAHs (O'Connell et al., 2014), flame retardants (Kile et al., 2016; Hammel et al., 2018), phthalates (Huang et al., 2017) and pesticides (Aerts et al., 2018; Fuhrimann et al., 2022). In a proof-of-principle study silicone pet tags were used to quantify cat exposure to flame retardants (Poutasse et al., 2019). This study showed the possibility of using silicone pet tags for measuring environmental exposures but did not explore the relevance of domestic animal exposure as a sentinel for human exposure.

In this study we hypothesize that domestic animals, in particular cats (e.g. Bost et al., 2016), can be used as sentinels to measure residential (house and close surroundings) exposure. To assess this, we focused our environmental exposure assessment on PAHs. Our objective was three-fold. Firstly, to devise sampling collars from silicone wristbands and evaluate their use for measuring environmental exposure in cats. Secondly, to compare exposure profiles between cats and humans using the collars and silicone wristbands, respectively. And thirdly, to study the determinants of both cat and human exposure.

2. Materials and methods

2.1. Study design

The study was executed between February and December 2018. Human-cat pairs were recruited through word of mouth and by veterinary doctors in one of three cooperating veterinary clinics. The study was exempted from Medical Research Involving Human Subjects Act (WMO) by the Medical Research Ethics Committee UMC Utrecht. Prior to enrollment the participants and researchers signed informed consents. Recruited participants ($N = 31$) resided either in cities (urban), outskirts (peri-urban) or villages (rural) in the provinces of North-Holland, Utrecht and North-Brabant, all located in the Netherlands.

2.2. Wristbands and collars

Pre-cleaned silicone wristbands were supplied by Oregon State University in two different sizes; one small size (1.9 × 11 × 177 mm) and a large size (1.9 × 11 × 210 mm). Silicone wristband pre-cleaning followed the method presented by Anderson et al. (2017). The wristbands were individually packed in polytetrafluoroethylene (PTFE) airtight bags and kept in a dark environment until deployment (not more than 72 h). To fit the silicone rubber on the collars, segments of silicone wristbands were carefully cut into pieces of 1.9 × 11 × 70 mm. We chose to attach the silicone to the outside of the collars with thread and needle, as cotton thread utilizes the least amount of coverage of the silicone's air-exposed surface, compared to cable ties or rivets, which may also cause discomfort to the animal. For the safety of the animals we decided to use collars with a safety lock, which are available in nylon and synthetic leather. Nylon proved to be the most efficient collar material for the attachment of silicone; unlike (synthetic) leather, nylon is easily penetrated with thread and needle. Moreover, synthetic leather is often made from polyurethane (Mohamed and Hassan, 2011), and could therefore compete with silicone in chemical (i.e. PAHs) adsorption. Before silicone attachment, collars and needles were immersed in a glass vial with n-Hexane and subjected to an ultrasone bath (Branson 5200 Ultrasonic Cleaner) at 25.000 Hz for 10 min. The solution was decanted and the collars were placed in a 37 °C incubator for 1 h to evaporate the remaining hexane. After this, one piece of silicone was tightly secured to each collar with thread and needle (visible in Supporting Information I, Fig. S1). The modified collars were then placed in plastic airtight containers and kept in dark until deployment.

The effect of any potential smells from the silicone or hexane treatment on cat behavior was tested prior to the start of the study. Two cats (that usually wear a collar) wore a collar fitted with the silicone rubber for 5 days. Their owners closely watched their behavior, which did not seem to be affected.

One non-deployed large wristband and one non-deployed clean silicone segment previously attached to a collar were used as blanks. Identical to the field samplers, the two blanks were kept in their containers and stored in a dark environment.

2.3. Questionnaires and diaries

Each participant completed a questionnaire and diary for the purpose of detecting possible exposure determinants. Questions were based on different existing questionnaires concerning human (e.g. Figueiredo et al., 2021) and cat activity (e.g. Strickler and Shull, 2014), and included questions on individual behaviors, smoking habits, living environment and building age. Diary questions described the time spent in- and outside, household activities (e.g. cooking with/without exhaust fan and frequency of vacuum cleaning)and number of showers taken. Both the questionnaire and diary included cat directed questions, such as cat age, sex and behavior. The questionnaire and diary (in the original language, i.e. Dutch) are included as supplement (Supporting Information II).

2.4. Sampling period

The wristbands and collars were worn for 7 consecutive days which allowed to measure a full week of exposure. Subjects were instructed to ignore the wristband as much as possible. Participants could therefore shower, swim and perform household tasks as to mimic actual bioavailable PAH exposure. After the 7-day study period, the participants placed the wristband and collar back in their individually packages and kept them in their refrigerator (approximately 4 °C) until pickup (max two days). Research material was transported in a cooling bag with ice packs before it was stored at −20 °C until analysis.

2.5. PAHs extraction, chemical analysis and quality control

Before extracting PAHs from the silicone rubbers, the samplers were placed in a 250 ml Erlenmeyer flask and infused with a known internal standard mix of 16 deuterium labeled PAHs. The samplers were left to adsorb the internal standard for 30 min. Then, 75 ml of acetonitrile (ACN) was added to each sampler and the flasks were placed on a shaker (Gerhardt: type RO 500) for 96 h at 120 rpm after which the extracts were transferred to another flask. This procedure was repeated once. To rinse off any remaining analytes, the samplers were carefully washed with 25 ml ACN. Each of the resulting extracts of 175 ml ACN was then reduced by evaporation to 1–2 ml in a rotary film evaporator (R-210 Rotavapor System with Vacuum Controller V-850, Heating Bath B-491 and Vacuum Pump V-700) (117 mbar, 45 °C). Next, 100 ml hexane was added to the extracts and attentively reduced to 1 ml by evaporation and transferred to gel permeation chromatography (GPC) injection vials. Extracts were then purified using GPC, in which desired molecular sizes were separated from larger unwanted molecules. This clean-up was executed on an Agilent 1100 series HPLC system with a PLgel 5 μl 50 Ǎ 300 × 7.5 mm (Agilent, Part no: 1110–6515) GPC column. The injection volume was 250 μl and column temperature 35 °C. Eluents consisted of (1) DCM (100%) and (2) Hexane/MTBE (1:1). Extract output was captured between 6.5 and 20 min after GPC initiation and reduced to 250 μl for Gas chromatography–mass spectrometry (GC-MS) analysis. GC-MS was performed on an Agilent type 7890 GC coupled to an Agilent Type 7000 triple quadrupole MS. The Ultra Inert (UI) GC-column was a

DB-5MS-UI (30 m × 0.25 mm, 0.25 μm). One μl of the extract was injected through cold spitless injection (cold injection at 40 °C–320 °C with rate 700 °C/min). The spectrometry temperature program and rate (°C/min) was as follows: initial temperature at 60 °C, and first, second and third cycles at 120 °C (rate 20 °C/min), 250 (rate 6 °C/min) and 300 °C (rate 17.5 °C/min) respectively. This approach was similar to that described by Wang et al. (2018).

The laboratory analyses were carried out under a quality system that complies with ISO 9001 (TNO). MS was performed in multiple reaction monitoring (MRM) acquisition mode. An overview of the MRM transitions along with the collision energies can be consulted in Supporting information III.

2.6. Handling left-censored values

PAH measurements below the limit of detection (LOD) were imputed following the method proposed by Lubin et al. (2004), which consists of fitting a model by maximum likelihood estimation by considering the distribution of the data above LOD. However, this was only done for PAHs with sufficient data to estimate the distribution (i.e. PAHs with detection frequency >50%). Those with a detection frequency of less than 50% are summarized but omitted from further analysis. Limits of quantification (LOQs) and LODs for the different PAHs can be consulted in Supporting information IV.

2.7. Statistical analysis

Statistical analysis were performed using the statistical computing R language, version 4.1.3 (R). PAH concentrations in the silicone rubbers were converted to *ng* (PAH)/*g* (Silicone rubber). The weight (in grams) of silicone rubber were measured in the lab prior to extraction. Field blank values were not subtracted from the samples due to the limited number of field blanks and since values were generally all below detection limit (n = 11 PAHs) or were very low as compared to measured concentration in field samples. The exception was naphthalene where an unexpected high concentration in the collar field blank was measured that was not mirrored by the blank wrist band (see Supporting Information V). All PAHs were log10 transformed to meet normality, and all further assumptions for the included statistical tests were met. Significance levels were based on $\alpha = 0.05$ (two tailed). Detection frequency differences between wristbands and collars were calculated using tests of equal proportions. Mean silicone PAH concentrations were compared using paired t-tests, with pairs being the cat and human in the same home. To determine the association between cat and human exposure, Spearman's rho correlation coefficients were calculated. Finally, the influence of different determinants (covariates) on PAH concentration variability was assessed by using a linear mixed effect model with house ID as random effect. A stepwise (bidirectional elimination) selection was performed. The model contained variables retrieved from the questionnaires, such as house age, frequency of changing bedsheets and vacuum cleaning, smoking habits. Given the number of predictors and small number of observations our multivariate analysis as a statistical power of 0.6. We provide the 95% confidence intervals as these reflect the smaller sample size.

3. Results & discussion

3.1. Characteristics of the human population

Of the 31 participants, 30 completed the 7-day sampling period. The median age of participants was (in years) 35.5 (range: 22–71), with most participants being female (N = 22, 73%). Nine participants (~30%) smoked. Two participants (6.7%) reported being frequently exposed to secondhand smoking. Overall, participants reported spending between 64% and 96% of their time inside their home during the sampling period (median: 86%).

3.2. Characteristics of the cat population

Out of the 31 participating cats, 30 completed the 7-day sampling period and had a filled in questionnaire and diary resulting in 30 cat-owner pairs. The median cats' age (in months) was 93 and out of the 30 cats, 19 (63%) were male. Overall, participants reported their cats spending between 43% and 99% of their time inside home during the sampling period (median: 90%). The participants were also asked to describe their cats energy within three categories: low, medium and high. More than half of the cats had medium energy (N = 17), with the remaining having low (N = 7) or high energy (N = 6). Cat energy might be important given that active cats alter between walking/sitting/laying/running more frequently. As a result, active cats will likely be in contact with different surfaces and will get exposed to resuspended particles more often.

3.3. detection and concentrations in cat collars and human wristbands

Out of the 16 analyzed PAHs, 15 were detected (at least one sample above LOD) in a total of 60 silicone samplers (30 human wristbands + 30 cat collars). Anthracene was the only PAH that was not detected in any of the samples. 14 PAHs were found in cat collars, of which only benzo[k]fluoranthene was unique to cats. Similarly, human wristbands had 14 different PAHs, of which acenaphthene was unique in humans. Detection frequencies were remarkably similar with the exception of benzo[g,h, i]perylene (BghiP) which was the only PAH that differed significantly in detection frequency between the two species (97% in humans vs. 63% in cats, $p = 0.004$). BghiP consists of 6 benzene rings and its predominant source in urban areas is vehicle exhaust (Lai et al., 2005; Swedish Environmental Protection Agency, 2009), and the [BghiP]/[benzo[e]pyrene] ratio is used as indicator of PAH source being traffic or non-traffic (Ohura et al., 2004). Even though we did not analyze benzo[e]pyrene, increased BghiP detection frequencies in human wristbands might have been a result of exposure to traffic. In fact, time spent outside did seem to be associated with increased BghiP concentrations in cat collars (supporting information VI). We also see that detection frequency of heavier (more than five rings) PAHs is similar to lighter PAHs, with the only significant difference being observed for Indeno[1,2,3-cd]pyrene. This result was not expected, as heavier PAHs predominantly occur particle bound and in this state they are less accessible to silicone adsorption (Paulik and Anderson, 2018). Therefore, we probably captured PAHs that got transferred from particulate matter to the silicone. This is however difficult to ascertain, since "it may be difficult to parse out whether direct particle partitioning into wristband or partitioning from air to wristband is the source of certain compounds" (cited from Hamzai et al., 2022).

Descriptive statistics and detection rates for all 15 PAHs are given in Table 1. After imputation, 9 PAHs were amendable to further statistical analyses. Boxplots with median and interquartile range of the concentrations of these 9 PAHs are shown in Fig. 1. Boxplots including discretization by smoking status of the household (i.e. smokers vs non-smokers) can be found in supporting information VII.

Overall, per PAH, concentrations were within the same order of magnitude for both cat collars and human wristbands. Detection frequency was very similar between the 9 imputed PAHs, however heavier PAHs (benzo[a]pyrene, indeno[1,2,3-cd]pyrene and BghiP) were detected in lower concentrations than lighter PAHs (higher vapor pressure), except for acenaphthylene. Human wristbands contained higher concentrations of BghiP, pyrene, indeno[1,2,3-cd]pyrene, fluoranthene, fluorene and phenanthrene as compared to the cats collar (all at $p < 0.001$). Like BghiP, these PAHs are also a result of incomplete combustion from, for example, engine exhaust.

Contrarily, naphthalene ($p < 0.01$) was captured in higher concentrations in cat collars. This finding could be associated with the high naphthalene concentrations in the collar blank and might be a result of contamination during collar preparation. Another explanation could be

Table 1
Descriptive statistics for the 15 different PAHs analyzed in wristbands worn by cats and humans.

PAHs [c]		Human wristbands (Hw)				Cat collars (Cc)					
	Number of benzene rings [a]	*AM (SD)*	*GM*	*Min - Max*	*% above LOD*	*AM (SD)*	*GM*	*Min - Max*	*% above LOD*	paired *t*-test (p-value)	Spearman Rho [d]
Imputed:											
Indeno[1,2,3-cd] pyrene	6	0.8 (1.9)	0.1	7E-3 – 10.0	57	0.6 (1.2)	0.1	2E-3 - 5.8	43	Hw > Cc (p < 0.01)	0.52
Benzo[g,h,i] perylene	6	0.9 (1.7)	0.4	8E-3 - 9.2	97	0.7 (1.2)	0.1	4E-3 - 5.6	63	Hw > Cc (p < 0.001)	0.50
Benzo[a]pyrene	5	0.5 (1.4)	0.1	8E-5 - 7.5	60	0.6 (1.2)	0.2	4E-3 - 5.5	77	p > 0.05	0.54
Fluoranthene	4	17.8 (13.4)	14.6	2.1–74.1	100	6.9 (5.9)	5.5	1.9–31.6	100	Hw > Cc (p < 0.001)	0.68
Pyrene	4	12.7 (9.6)	9.0	0.1–50.2	97	5.1 (4.3)	4.2	2.0–23.3	100	Hw > Cc (p < 0.001)	0.40
Phenanthrene	3	52.5 (26.9)	45.4	11.0–143.2	100	16.6 (5.7)	15.8	10.1–33.3	100	Hw > Cc (p < 0.001)	0.51
Fluorene	3	5.8 (2.4)	5.4	3.0–14.5	100	3.8 (1.0)	3.7	2.4–6.5	100	Hw > Cc (p < 0.001)	0.53
Naphthalene	2	4.3 (2.1)	3.9	1.9–12.0	100	10.7 (6.1)	9.5	4.5–29.8	100	Cc > Hw (p < 0.001)	0.16
Acenaphthylene	2[b]	0.8 (0.9)	0.5	0.1–3.8	100	0.6 (0.6)	0.4	0.1–3.0	90	p > 0.05	0.46
Non-imputed:											
Benzo[b] fluoranthene	5	ND	ND	<LOD - 4.9	7	ND	ND	<LOD - 3.6	7	ND	ND
Benzo[k] fluoranthene	5	ND	ND	<LOD	0	ND	ND	<LOD - 4.0	7	ND	ND
Dibenz[a,h] anthracene	5	ND	ND	<LOD - 3.8	17	ND	ND	<LOD - 3.1	23	ND	ND
Benz[a]anthracene	4	ND	ND	<LOD - 17.6	27	ND	ND	<LOD - 11.2	37	ND	ND
Chrysene	4	ND	ND	<LOD - 20.1	10	ND	ND	<LOD - 22.3	17	ND	ND
Acenaphthene	3	ND	ND	<LOD - 3.0	7	ND	ND	<LOD	0	ND	ND
Anthracene	3	ND	ND	<LOD	0	ND	ND	<LOD	0	ND	ND

All values are in ng/gram of material collected from the silicone rubbers. AM – arithmetic mean; SD – standard deviation; GM – geometric mean; LOD – limit of detection; ND – not determined; Hw – Human wristbands; Cc – Cat collars; a Ref: Petrovic et al., (2007)/b Acenaphthylene contains 2 aromatic and 1 non-aromatic ring./c PAHs ordered by imputed and non-imputed and by number of benzene rings (descending)/d Spearman correlation between paired Hw and Cc.

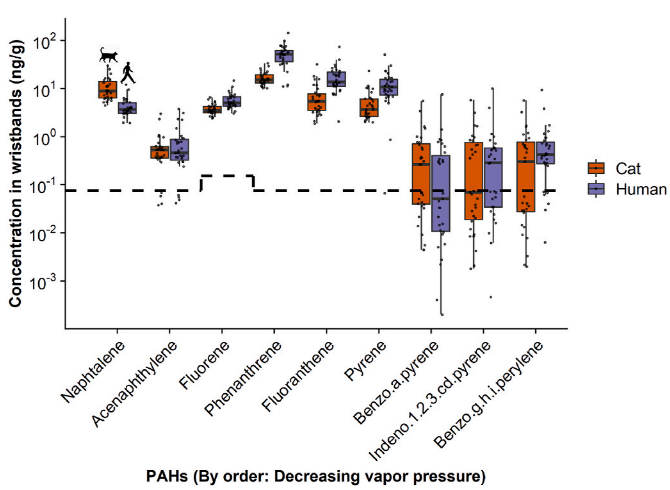

Fig. 1. Concentration of 9 different PAHs in wristbands worn by cats and humans. Summary statistics in boxplots (min, max, 1st and 3rd quartile and median). The dotted line refers to the detection limit (LOD) of each PAH. In the x-axis the name of the different PAHs (ordered by decreasing vapor pressure, left to right). In the y-axis the log10 transformed concentration in wristbands (in nanogram/gram of material collected from the wristband).

that naphthalene could come from mothball degradation (DeClementi, 2005), however we could not assess this since we did not collect information on use of mothballs.

There are some studies (N = 13, Scopus) that have employed wristbands for human PAH exposure assessment. As wear time and exposure setting differ between these studies direct comparisons are difficult. Mendoza-Sanchez et al. (2022) quantified maternal PAH exposure by having wristbands worn for three nonconsecutive 24-h periods. In that study, PAHs concentrations were a factor 5 higher than those measured in our study, with the exception for 5–6 ring PAHs, like BghiP. Baum et al. (2020) measured PAHs using wristbands in firefighters that reported being in action. The reported levels were overall a factor 2 to 5 higher than those measured in our study, with the exception of phenanthrene. It is important to stress that both the above mentioned studies were performed in the US, so a direct comparison of results might not represent the full picture given that the source strength could be quite different (e.g. Li et al., 2021).

3.4. Correlation between and within human wristbands and cats collars

Correlations between cat collars and human wristbands for the same PAHs was overall fair/moderate (median rho: 0.51 range, 0.16–0.68). Most PAHs, with exception of Naphthalene, showed good agreement between the two species (Panel A, Fig. 2). Hence, these results show that cats can be used as proxies for humans in residential exposure of almost

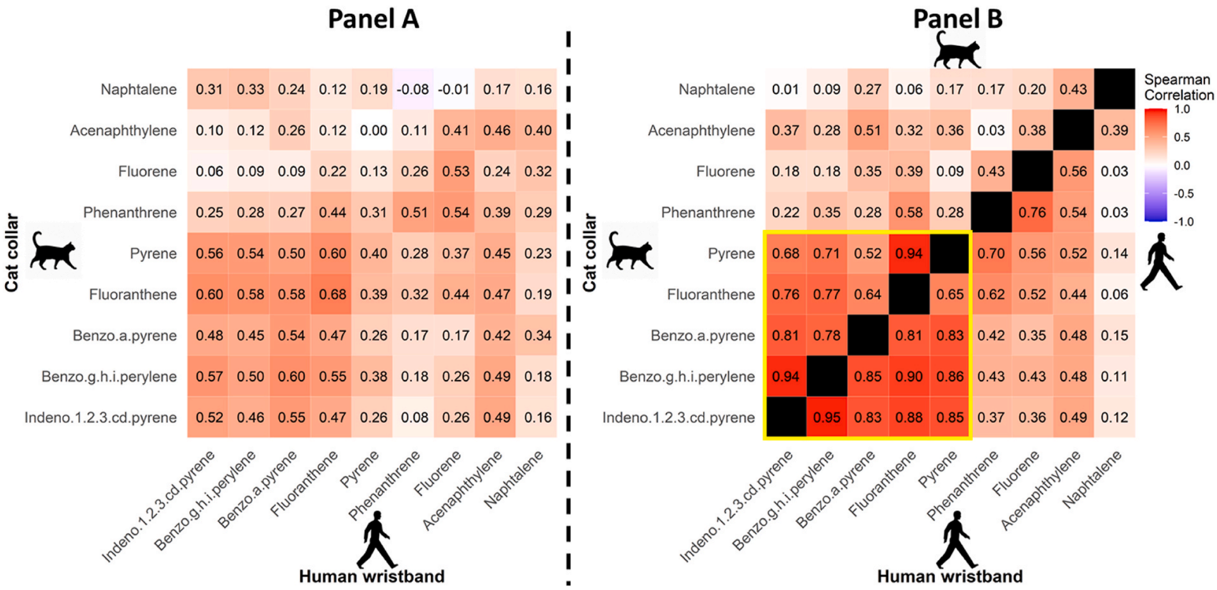

Fig. 2. Heatmap of Spearman correlation coefficients between the concentrations of the 9 different imputed PAHs. In panel A, correlations of the different PAHs between species, with cats on the y axis and humans on the x axis. In panel B, correlations of the different PAHs within species. For panel B, within cat correlations are presented on upper diagonal matrix and within human correlations are presented on the lower diagonal matrix. PAHs are ordered in both axes by decreasing vapor pressure. The yellow square in Panel B represents a cluster of correlations all above 0.5 for both species.

all PAHs, with exception of naphthalene. Naphthalene was also the only PAH that was detected in significantly higher concentrations in cats than in human wristbands. This difference could indicate that some exposure source(s) of naphthalene might not be shared between cats and humans. (See matrix Panel A, Fig. 2 and Table 1). As mentioned above, mothballs can be one of this different exposure sources.

When looking at PAHs correlations within species (see matrix Panel B, Fig. 2), we found overall moderate to high correlations between the different PAHs measured both in cat collars and human wristbands. Correlations are higher (Spearman rho range: 0.52–0.94 for cats and 0.65–0.95 for humans) between heavier PAHs (i.e. 4 or more benzene rings) (see highlighted box in Panel B, Fig. 2), indicating possible common exposure sources to these group of PAHs. This is likely due to the fact that heavier PAHs are more persistent in the environment than lighter PAHs (Fu and Suuberg, 2011). Overall these results show that cats can be used as proxies for humans in residential exposure of almost all PAHs, with exception of naphthalene.

3.5. Determinants of PAH concentrations variability

Determinants affecting PAH concentration were identified using a multivariate stepwise regression model. Models were built for cats (Table 2) and humans (Table 3). For cats, selected variables were often similar between the different PAHs and for most cases presented the same coefficient direction. Results show that, across all PAHs, three main variables were associated with a decrease in concentrations: 1) increased frequency of bedsheets cleaning; 2) higher time spent indoors by the cat and 3) being a female cat. Bedsheets act as a surface for house dust to settle on (Yang et al., 2015), and regular changing of bedsheets may lower dust accumulation. Our results show that higher time spent indoors likely reflects lower exposure to heavier PAHs, which is likely due to reduced exposure to car exhaust. Interestingly, cat sex was not previously discussed in the literature regarding exposure differences. This might be related with cat behavior, given that males usually tend to have higher ranges (kilometers away from home) than females (Lepczyk et al., 2015), thus increasing likelihood of exposure to different sources of PAHs. Vacuum cleaning was associated with an increase in concentrations. As vacuum cleaning increases resuspension of previously deposited dust (Vicente et al., 2020) this may lead to temporarily higher airborne exposures, here captured by the wristbands.

For humans, identified exposure determinants were more diverse between the different PAHs and coefficient directions were less consistent. Increased frequency of bedsheets cleaning was associated with lower concentrations. Living in a city increased concentrations of two PAHs (i.e. acenaphthylene and phenanthrene) while smoking increased the concentration of heavy PAHs, namely benzo[a]pyrene and indeno [1,2,3-cd]pyrene. This last finding was also seen for cats. However, smoking status was a determinant for naphthalene concentrations in cat collars but not in human wristbands. Cigarette smoke is a known contributor to naphthalene exposure of humans (Preuss et al., 2003), but there was no significant difference between smokers and non-smokers naphthalene exposure for humans (see Fig. S3, Supporting Information VII). The fact that humans spent more time outdoors than cats and are exposed often to other sources of naphthalene (e.g. car exhaust) might attenuate hide the effect of cigarette smoking in exposure to naphthalene for humans.

Finally, age and height were also selected as important determinants for some PAHs for humans. Regarding age, we found studies where age was a determinant for different PAHs metabolite concentrations in urine (e.g. Keir et al., 2021). However, in these studies age is a proxy for the differences in metabolism. In our case, age might be associated with quotidian differences (e.g. different hobbies, different work places, etc …). We found only one other study that saw a significant correlation between age and external exposure to PAHs. Here exposure was measured via questionnaire (Pavanello et al., 2020). Regarding height, the findings are contradictory, for some PAHs there is a negative association with height (e.g. Fluorene), whilst for others this is a positive association (e.g. Indeno[1,2,3-cd]pyrene). We only found one other study that saw PAH levels in blood as being negatively associated with child height (Xu et al., 2015). Height might also be a proxy for proximity to different contaminated surfaces (e.g. floor), however we could not assess this.

Table 2
Determinants selected in the stepwise regression model for cats.

Determinants [a]	Cat collars								
	Naph	Acen	Fluore	Phen	Fluora	Pyr	Bap	Ind	Brp
Sex									
Male		Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.
Female		−0.02 (−0.46–0.10)	−0.06 (−0.14–0.02)	−0.11[b] (−0.20 to −0.02)	−0.24[b] (−0.44 to −0.04)	−0.22[b] (−0.42 to −0.03)	−0.73[b] (−1.35 to −0.12)	−0.67[b] (−1.21 to −0.13)	−0.45 (−0.97–0.07)
House location									
Suburbs			Ref.						
City			0.02 (−0.06–0.10)						
Rural/ Village			0.15[b] (0.04–0.26)						
Couch age	−0.02[b] (−0.03-4E-3)		9E-3[b] (2E-3-0.02)	0.02** (7E-3- 0.02)	0.02 (-1E-3-0.03)	0.02 (-2E-3-0.03)	0.03 (−0.02–0.09)		
Smoking status									
No	Ref.						Ref.	Ref.	Ref.
Yes	0.22** (0.06–0.38)						0.61[b] (0.07–1.15)	0.61[b] (0.07–1.14)	0.49 (−0.10–1.08)
% Time spent indoors (by cat)		−0.79 (−1.83–0.25)			−0.85** (−1.33 to −0.38)	−0.64** (−1.10 to −0.17)	−3.23** (−5.40 to −1.07)	−4.75** (−6.75 to −2.74)	−4.44** (−6.39 to −2.50)
% Time spent indoors (by human)		2.03 (−0.22–4.29)	0.46[b](0.02–0.90)				2.64 (−1.83–7.12)	2.88 (−1.34–7.10)	3.96[b] (0.08–7.81)
Number of inhabitants							0.06 (−0.02–0.14)		
Vacuum count	−0.05 (−0.11-1E-3)	0.10[b] (5E-3-0.20)	0.03[b] (2E-3-0.05)	0.04[b] (0.01–0.08)	0.08[b] (0.02–0.13)	0.07[b] (0.01–0.13)			0.13 (−0.06–0.32)
Clean bedsheets									
once or less a month		Ref.	Ref.	Ref.	Ref.	Ref.		Ref.	
2 to 4 times a month		−0.34 (−0.74–0.07)	−0.11[b] (−0.21- -5E-3)	−0.21** (−0.31 to −0.1)	−0.24[b] (−0.47- -8E-3)	−0.25[b] (−0.47 to −0.02)		−0.52 (−1.27–0.23)	
Perceived cat energy									
medium		Ref.					Ref.		
low		0.43[b] (0.08–0.78)					−0.60 (−1.30–0.10)		
high		0.14 (−0.21–0.48)					−0.24 (−0.89–0.40)		

Legend: Naph – Naphthalene; Acen – Acenaphthylene; Fluore – Fluorene; Phen – Phenanthrene; Fluora – Fluoranthene; Pyr – Pyrene; Bap - Benzo[a]pyrene; Ind - Indeno[1,2,3-cd]pyrene; Brp - Benzo[g,h,i]perylene.

[a] *For each selected determinant the results are presented by the beta regression coefficient (β) and 95% Confidence intervals (i.e. β (95% CI)).*

[b] p-value <0.05; ** p-value <0.01.

3.6. Study strengths and limitations

To the best of our knowledge, this is the first study to measure environmental exposure by deploying wristbands parallel in humans and their domestic cats. The strength of the study design is that the wristbands were deployed during the same period in both species and there were no major residential PAH sources reported (e.g. barbecuing) during the study period. Moreover, we were able to look at determinants of exposure across species, which can be quite relevant for intervention studies. Finally, the design of the cat collar sampler allows to assess close contact with fur (dermal adsorption via skin contact) besides the inhalation route, while all other studies that have deployed silicone samplers in domestic animals used tags (e.g. Wise et al., 2022), which are not in contact with the body surface and therefore might not capture as well the dermal absorption route. An additional possibility for cat collar design would be to have the whole collar made of silicone, however we were not sure how this would affect cats behavior and if it would meet safety guidelines. This should be explored in future studies.

This study also comes with certain limitations. Foremost, seven days may be too short to measure residential concentrations of heavy PAHs. Furthermore, silicone adsorbs chemicals from dermal and inhalation routes but might not be representative of exposure from dust ingestion, which is an important pathway in cats' chemical exposure (Weiss et al., 2021). Hence measuring with silicone may not reflect total exposure. We measured one high concentration value of naphthalene in the cat collar blank, so results regarding naphthalene need to be interpreted with caution in the event of possible contamination. The mixed models include 8 covariates and a small set of observations, so interpretation of results should take into account the 95% confidence intervals. Lastly, we used PAHs concentrations as the proof-of-principle that cats can be used as sentinels for residential human exposure. However, this may not be the case of all environmental exposures. Therefore additional studies looking at a broader range of chemicals are required.

Table 3
Determinants selected in the stepwise regression model for humans.

Determinants [a]	Human wristbands								
	Naph	Acen	Fluo	Phen	Fluo	Pyr	Bap	Ind	Brp
Age	-4E-3** (-7E-3- -1E-3)	-8E-3* (−0.01- -7E-4)				−0.01 (−0.02-3E-3)			
Height	−0.01* (−0.02- -5E-3)	−0.02* (−0.03- -6E-4)	-7E-3* (−0.01- -1E-3)		7E-3 (-3E-3-0.02)		0.05* (7E-3-0.10)	0.06** (0.02–0.10)	
Weight			-3E-3 (-7E-3-8E-3)						
Sex									
Male							Ref.	Ref.	Ref.
Female							1.35** (0.38–2.32)	0.82 (−0.07–1.71)	0.31 (−0.18–0.81)
House location									
Suburbs		Ref.		Ref.					Ref.
City		0.46** (0.18–0.74)		0.34* (0.10–0.59)					0.05 (−0.43–0.53)
Rural/Village		−0.02 (−0.43–0.39)		0.21 (−0.12–0.54)					−0.55 (−1.25–0.14)
Couch age				0.01 (-6E-3-0.03)					−0.02 (−0.06–0.02)
Smoking status									
No			Ref.	Ref.			Ref.	Ref.	
Yes			−0.06 (−0.15–0.03)	−0.23 (−0.48-4E-3)			0.93* (0.09–1.78)	0.93** (0.26–1.60)	
% Time spent indoors (by cat)	0.25 (−0.1–0.6)	−2.50** (−3.43 to −1.58)	−0.21 (−0.45–0.04)						
% Time spent indoors (by human)	−0.81* (−1.56 to −0.04)	2.02* (0.15–3.90)							−2.11 (−4.82–0.59)
Number of inhabitants	−0.01 (−0.03- - 2E-3)		0.01* (1E-3-0.02)	0.03* (3E-4-0.05)					
Vacuum count	0.03*	0.10* (0.02–0.19)		0.09* (0.02–0.17)	0.09** (0.03–0.16)		0.22 (−0.04–0.49)		0.11 (−0.04–0.26)
Clean bedsheets									
once or less a month	Ref.	Ref.	Ref.						Ref.
2 to 4 times a month	−0.36** (−0.50 to −0.23)	−0.61** (−1.02 to −0.20)	−0.31** (−0.43 to −0.19)						−0.68* (−1.31 to −0.05)
Perceived cat energy									
Medium							Ref.	Ref.	
Low							−0.73 (−1.57–0.11)	−0.59 (−1.32–0.14)	
High							−0.03 (−0.87–0.80)	0.11 (−0.65–0.89)	
Number of showers	0.01 (-4E-3-4.45)	0.03 (−0.02–0.09)		0.03 (-5E-3-0.07)		−0.06 (−0.13–0.02)	−0.10 (−0.24–0.03)	−0.13* (−0.25 to −0.1)	

* p-value <0.05; ** p-value <0.01.
Legend: Naph – Naphthalene; Acen – Acenaphthylene; Fluore – Fluorene; Phen – Phenanthrene; Fluora – Fluoranthene; Pyr – Pyrene; Bap - Benzo[a]pyrene. Ind - Indeno[1,2,3-cd]pyrene; Brp - Benzo[g,h,i]perylene.
[a] *For each selected determinant the results are presented by the beta regression coefficient (β) and 95% Confidence intervals (i.e. β (95% CI)).*

4. Conclusions

Using silicone samplers we assessed PAH residential exposures of both cats and humans. We detected several PAHs in both wristbands and cat collars. Moderate correlations between cats and humans were found for most of the PAHs. Adding to this, determinants of variability in measured concentrations were often similar between both humans and cats. Both these results strengthen the fact that cats might be good sentinels for human residential (i.e. home and close surroundings) exposure when performing environmental sampling in a residential setting. Hence, besides using the collars to investigate links between cat health and PAH exposure, they could also be used to study links between human exposure and health.

Funding

Internal funds from the Institute for Risk Assessment Sciences (Utrecht University).

Author contribution

Daniel Figueiredo: Conceptualization, Methodology, Resources, Visualization, Validation, Formal analysis, Supervision, Data curation, Writing - original draft, Writing - review & editing, Formal analysis, Investigation. **Serigne Lô**: Execution, Methodology, Resources, Formal analysis, Data curation, Writing - original draft, Writing - Review & Editing. **Esmeralda Krop**: Resources, Data curation, Writing - Review & Editing. **Jack Spithoven**: Methodology, Resources. **Jeroen Meijer:**

Investigation, Writing - Review & Editing. **Henry Beeltje:** Investigation, Resources, Data curation. **Marja Lamoree:** Investigation, Writing - Review & Editing. **Roel Vermeulen**: Conceptualization, Methodology, Writing - Review & Editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgment

The authors would like to thank the participants for their enrolment in the study and TNO for the laboratory analysis of the wristbands. We thank Jack Spithoven for the help during the collars preparation. We thank Marieke Oldenwening and Marjan Tewis for the help with the ethical approval document and setting up the field work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2023.115412.

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