

A novel ambient air sampler for detection of allergens and endotoxin



Maria A. Oliver, PhD,^a Rhys T. Meredith, MRes,^a Max D. Bermingham, MPhil,^a Emily K. Sturt, BSc,^a Emily A. Heath, PhD,^a Stephanie C. Filep, BSc,^b Anna Kuklinska-Pijanka, MSc,^a Ross A. R. Yarham, BSc,^a Hayley Mills, PhD,^a and Martin D. Chapman, PhD^b *Cardiff, United Kingdom; and Charlottesville, Va*

Background: Current methods for measuring airborne allergen and endotoxin exposure in indoor environments rely on air sampling (using flow rates traditionally lower than 10 L/min) or using settled dust as a proxy, both of which have limitations. **Objectives:** We sought to develop a novel, user-friendly ambient air sampling device (ambient air sampler [AAS]) for accurate and efficient measurement of allergens and endotoxin.

Methods: The AAS is a small, quiet, lightweight device that draws air at a high flow rate (>500 L/min) across a filter to collect airborne particles. AAS devices sampled homes across South Wales, UK, and Central Virginia, USA. Devices were run alongside Institute of Occupational Medicine samplers, with both operating for 10 hours. Devices were also operated for 7 days alongside electrostatic dust collectors, which passively sampled the environment for the equivalent time. Following extraction, indoor and food allergens were quantified by multiplex assays and ELISA. Endotoxin was measured using Recombinant Factor C assay.

Results: After 10 hours, the AAS collected 13 allergens from dust mite, cat, dog, mouse, and multiple foods, with positivity rates up to 100%. In comparison, Institute of Occupational Medicine samplers collected 5 allergens in total, with much lower positivity rates. After 7 days, the AAS collected 10 different indoor allergens and 13 different food allergens across UK and US homes. Allergens from cat, dog, milk, egg, and peanut were collected in almost every home. The AAS collected all allergens more frequently and in significantly higher amounts than the electrostatic dust collectors. The AAS also collected airborne endotoxin in every home sampled, from as little as 1-day sampling time.

Conclusions: The AAS developed herein provides a standardizable method for monitoring airborne allergen and endotoxin exposure, with potential applicability to other biological environmental agents. (*J Allergy Clin Immunol Global* 2026;5:100677.)

Key words: Aeroallergens, airborne endotoxin, air sampler, environmental exposure, multiplex array

Abbreviations used

AAS: Ambient air sampler

EDC: Electrostatic dust collector

IOM: Institute of Occupational Medicine

Exposure to environmental allergens such as house dust mites, pets, and pests is strongly associated with the development of allergic diseases, including allergic rhinitis and asthma.¹⁻³ Monitoring of environmental allergen exposure has been a cornerstone of clinical, epidemiologic, and occupational studies of asthma and intervention control.⁴⁻⁶ Measuring allergen content in reservoir dust samples allowed allergen exposure assessments to be standardized and thus risk levels and avoidance recommendations were developed, yet there are known limitations to this method.^{3,7,8} Household dust samples from different locations within the home are heterogeneous and the amount of dust collected varies between sampling sites (eg, mattresses, furnishings, and carpets). Because inhalation is the primary route of exposure for developing respiratory allergy, investigators have long sought to develop reliable methods for monitoring airborne allergen exposure.⁴ The relationship between allergen content in settled dust samples and air samples is complex and results do not always correlate.⁹⁻¹² This is partially due to different aerodynamic properties of the particles that carry airborne allergens. Dust mite allergens originating in mite feces of 10 to 40 μm diameter remained airborne for 20 to 40 minutes, whereas cat and dog dander allergens found on 2- to 10- μm particles remained airborne for several hours.¹³⁻¹⁸ The particle sizing equipment used for those studies, for example, cascade impactors and Anderson samplers, is not suitable for routine collection and monitoring of air samples. The criterion standard for personal air samplers is the Institute of Occupational Medicine (IOM) sampler—a lapel-worn filter collection device that samples air in the personal breathing zone at a rate of approximately 2 L/min using pumps. These are used to measure occupational exposure to animal allergens in laboratory animal facilities and in assessments of other workplace exposures.¹⁹⁻²² Downsides of IOM samplers are that they are cumbersome to the user, the associated pumps are noisy, and they are designed for relatively short sampling periods. Recently, electrostatic dust collectors (EDCs) have been used to passively adsorb allergens that settle from the air onto polyester cloths and are considered a useful surrogate for indoor airborne exposure.^{12,23} Disadvantages of EDCs include the inability to calculate the volume of air from which settled particles derived, and the concentration of allergen on the cloths is often below the level of detection.^{4,12}

From ^aInBio, Cardiff; and ^bInBio, Charlottesville, Va.

Received for publication September 29, 2025; revised November 12, 2025; accepted for publication January 9, 2026.

Available online February 24, 2026.

Corresponding author: Maria A. Oliver, PhD, InBio, Vision Court, Caxton Place, Cardiff CF23 8HA, UK. E-mail: moliver@inbio.com.

The CrossMark symbol notifies online readers when updates have been made to the article such as errata or minor corrections

2772-8293

© 2026 The Author(s). Published by Elsevier Inc. on behalf of the American Academy of Allergy, Asthma & Immunology. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

<https://doi.org/10.1016/j.jacig.2026.100677>

Abbreviations used

AAS: Ambient air sampler

EDC: Electrostatic dust collector

IOM: Institute of Occupational Medicine

In addition to aeroallergens, airborne endotoxin exposure has been linked with asthma and other respiratory diseases.^{24,25} However, there is a lack of standardization for measuring airborne endotoxin exposure in homes, offices, and schools, with various different equipment having been used previously, including filters attached to sampling pumps, impingers, and EDCs.^{23,26}

Here, we report a novel standalone ambient air sampling device (ambient air sampler [AAS]) that has a large sample collection filter, high flow rate (without associated pumps), and quiet operation. Significant improvements in aeroallergen monitoring were obtained by combining efficient air sampling using the AAS with sensitive multiplex immunoassays for measuring indoor and food allergens. In this pilot study of allergen exposures in US and UK homes, the AAS was validated by comparison with IOM and EDC samplers.

METHODS**Ambient air sampler**

The novel AAS device (GX Group, Usk, UK) is small, lightweight, and quiet (see [Table I](#) and [Fig 1](#) for specifications). The fan inside the device pulls ambient air across a nonwoven polypropylene filter (sampling surface area of 61 cm²) mounted onto a filter holder at an air flow rate of 532 L/min ([Table I](#)).

Air sampling

AAS devices were placed in homes located in South Wales, UK (n = 18), and Central Virginia, USA (n = 19). For further details, see this article's Methods section in the Online Repository at www.jaci-global.org.

AAS devices were positioned in living areas of 12 UK homes alongside IOM sampling heads (SKC, Blandford Forum, Dorset, UK), attached to an SKC Sidekick pump calibrated to 2 L/min. Both samplers were run for 10 hours. AAS devices and EDCs (Swiffer, El Paso, Tex) were placed side by side in 37 homes (United Kingdom and United States). The AAS device was switched on, and both sampled the environment for 7 days. For longitudinal endotoxin sampling, AAS devices were placed side by side in 12 UK homes. Filters were removed at different sampling time points. For further details of sampling, see this article's Methods section in the Online Repository.

Allergen extraction

AAS filters, IOM filters, and EDCs were extracted in PBS with 0.05% Tween, pH 7.4, in volumes of 10, 1, and 25 mL, respectively. All filters/EDCs were extracted for 2 hours at room temperature with gentle agitation. Supernatants were transferred to cryovials and stored at -20°C until analysis. Blank filters and EDCs were extracted in the same way to act as controls.

Multiplex array for indoor and food allergens

For the detection of indoor allergens (Der p 1, Der f 1, Mite Group 2 [dust mite], Fel d 1 [cat], Can f 1 [dog], Mus m 1

TABLE I. Specifications of the AAS device

Dimensions	12.1 cm × 11.0 cm × 6.4 cm (Height × Width × Depth)
Weight	301 g (device plus filter holder) (n = 13, Min 301 g, Max 301 g, Range 0 g)
Decibels	41 dB* (n = 13, Min 40 dB, Max 42 dB, Range 2 dB)
Air flow	532 L/min† (n = 72, Min 506 L/min, Max 555 L/min, Range 49 L/min)

Max, Maximum; Min, minimum.

*Measured with a Tadeto sound level meter #SL720, 50 cm from device.

†Measured with an adapted Mastech digital anemometer #MS6252A.

[mouse], Rat n 1 [rat], and guinea pig urinary protein [guinea pig]), a multiplex array based on the Luminex xMAP system (Luminex Corporation, Austin, Tex) was used as previously described.^{27,28} Blank filters were also analyzed as sampling controls (all allergens were below lower limit of detection; see this article's Results section and [Table E1](#) in the Online Repository at www.jaci-global.org). For food allergen detection (Bos d 5, Bos d 11 [milk], Gal d 1 and Gal d 2 [egg], Ara h 3 and Ara h 6 [peanut], Ana o 3 [cashew], Pru du 6 [almond], Jug r 1 [walnut], Cor a 9 [hazelnut], Ses i 1 [sesame], Sin a 1 [mustard], Shrimp tropomyosin, and Gly m 5 [soy]), a modified version of this multiplex array was used as previously described.^{29,30} Blank filters were also analyzed as sampling controls (all allergens were below lower limit of detection except Bos d 11; see this article's Results section and [Table E1](#) in the Online Repository). Allergen concentration in nanogram of allergen per milliliter (ng/mL) was calculated from control curves of purified allergens and converted to nanogram of allergen per sample (ng/sample). For the 10-hour samples, a further conversion to picogram of allergen per cubic meter (pg allergen/m³) was made. For example calculations, see this article's Methods section in the Online Repository.

ELISA for Ory c 3 (rabbit) and Equ c 1 (horse)

For the detection of major rabbit and horse allergens Ory c 3 and Equ c 1, an ELISA 2.0 kit (InBio, Charlottesville, Va) was used according to manufacturer's instructions. Allergen concentration in the samples was calculated as nanogram of allergen per milliliter from control curves and converted to nanogram of allergen per sample.

Endotoxin assay

Endotoxin was measured using the ENDOZYMYE II Recombinant Factor C Endotoxin Detection Assay (BioMérieux, Lyon, France) according to the manufacturer's instructions. Endotoxin concentration was calculated from the standard curve and expressed as endotoxin units per filter (EU/filter).

Statistics

GraphPad Prism V10.1.2 (GraphPad Software, LCC, Boston, Mass) was used for statistical analyses. For further details of statistical analysis, see this article's Methods section in the Online Repository.

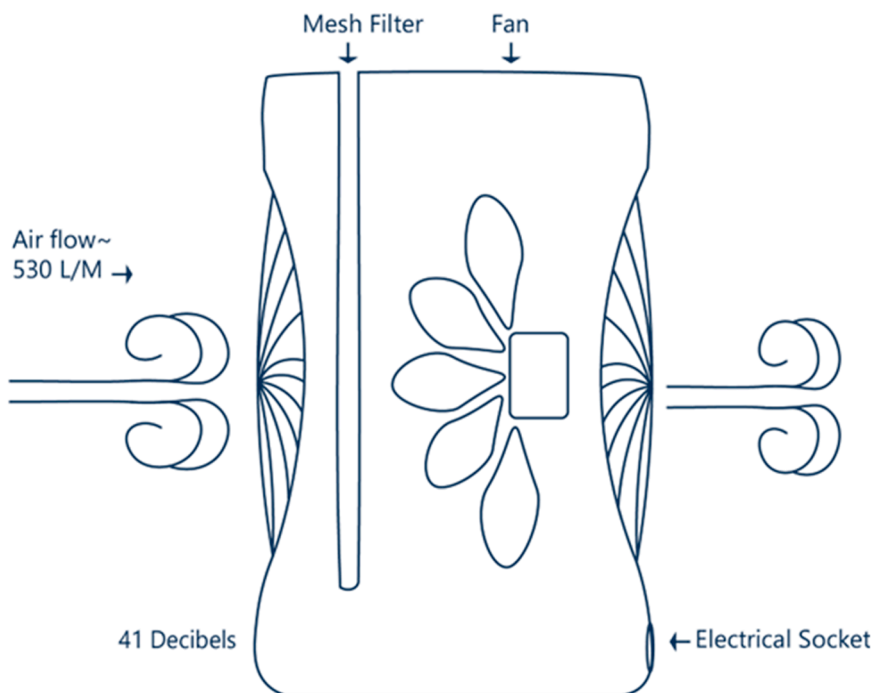


FIG 1. Diagram of the novel AAS. Air is drawn in through the front of the AAS by an internal fan and across a mesh filter, which captures aeroallergens and airborne endotoxin (not drawn to scale).

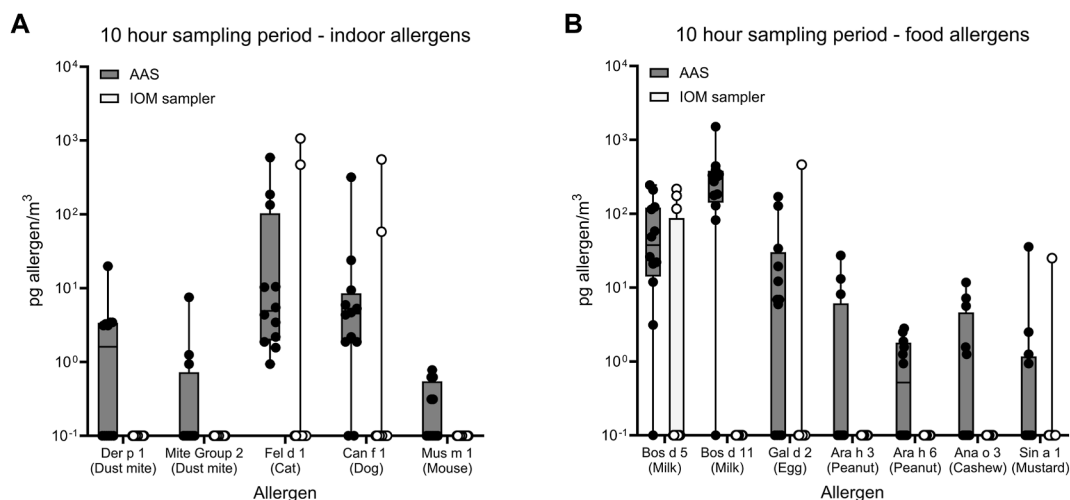


FIG 2. Measurement of aeroallergens after a 10-hour sampling period. Indoor (A) and food (B) allergens captured by AAS devices (dark gray bars, solid symbols) and IOM samplers (light gray bars, open symbols) after 10 hours of sampling. Results expressed as pg allergen/m³. Arbitrary value of 0.1 was assigned for any sample below lower limit of detection. Jug r 1 data not shown.

RESULTS

Comparison of the AAS with an IOM sampler

AAS devices and IOM samplers were placed in 12 homes across South Wales, UK. After 10 hours of sampling, 5 different indoor allergens were collected by the AAS device (Fig 2, A, and Table II). Dust mite allergens Der p 1 and Mite Group 2 were collected in 50% and 25% of homes, respectively. Fel d 1 (cat) and Can f 1 (dog) were collected in 100% and 83% of homes, respectively, despite there being only 3 cat owners and 2 dog owners. Low levels of Mus m 1 (mouse) were collected in 42% of properties. In comparison, the IOM samplers did not collect

detectable levels of dust mite or mouse allergens in any home, and cat and dog allergens were collected only in those homes where these pets resided.

Eight food allergens were collected using the AAS device: Bos d 5, Bos d 11 (milk), Gal d 2 (egg), Ara h 3 and Ara h 6 (peanut), Ana o 3 (cashew), Sin a 1 (mustard), and Jug r 1 (walnut) (Fig 2, B, and Table II). Bos d 5 and Bos d 11 were collected in 91% of homes sampled, and Gal d 2 was collected in 67% of homes. In comparison, only Bos d 5, Gal d 2, and Sin a 1 were collected by the IOM samplers at lower positivity rates (25%, 8%, and 8% of homes, respectively).

TABLE II. Indoor and food allergens captured by AAS and IOM samplers after a 10-hour sampling period

Category of allergen	Source	Allergen	Positivity rate		Average pg/m ³	
			AAS	IOM sampler	AAS	IOM sampler
Indoor allergens	Dust mite	Der p 1	50% (6 of 12)	0% (0 of 12)	3.1	0.1*
		Mite Group 2	25% (3 of 12)	0% (0 of 12)	0.9	0.1*
	Cat	Fel d 1	100% (12 of 12)	17% (2 of 12)	79	128
	Dog	Can f 1	83% (10 of 12)	17% (2 of 12)	31	51
	Mouse	Mus m 1	42% (5 of 12)	0% (0 of 12)	0.3	0.1*
Food allergens†	Milk	Bos d 5	91% (11 of 12)	25% (3 of 12)	74	42
		Bos d 11	91% (11 of 12)	0% (0 of 12)	348	0.1*
	Egg	Gal d 2	67% (8 of 12)	8% (1 of 12)	32	39
	Peanut	Ara h 3	25% (3 of 12)	0% (0 of 12)	4.1	0.1*
		Ara h 6	50% (6 of 12)	0% (0 of 12)	1.0	0.1*
	Cashew	Ana o 3	42% (5 of 12)	0% (0 of 12)	2.3	0.1*
	Walnut	Jug r 1	8% (1 of 12)	0% (0 of 12)	0.3	0.1*
	Mustard	Sin a 1	34% (4 of 12)	8% (1 of 12)	3.4	2.2

Positivity rate is expressed as a percentage, with the number of positive homes out of the total number sampled shown in parentheses. Average amount of allergen is expressed as picogram of allergen per cubic meter (pg/m³).

LLOD, Lower limit of detection; STM, Shrimp tropomyosin.

*All results <LLOD were assigned an arbitrary value of 0.1.

†Also analyzed: Pru du 6, Cor a 9, Gal d 1, Ses i 1, STM, and Gly m 5—all results <LLOD.

Comparison of the AAS devices with EDCs

AAS devices and EDCs were placed in 37 homes across South Wales, UK, and Central Virginia, USA. After sampling for 7 days, 6 indoor allergens were collected by the AAS device and the EDCs in both locations (Fig 3, A, and Table III). In UK homes, 81% of homes were positive for at least 1 dust mite allergen. In US homes, this figure was 32%. In comparison, EDCs collected dust mite allergens in far fewer homes in both the United Kingdom and the United States, 22% and 16%, respectively. Cat and dog allergens were collected in 89% of homes sampled using the AAS device, despite only 30% of homes owning a cat(s) and 43% of homes owning a dog(s). The EDC collected Fel d 1 in a similar number of homes as the AAS device (81%) but Can f 1 was collected in far fewer homes (50%). Low levels of mouse allergen were collected in 32% of homes when sampled by the AAS device in comparison to 16% of homes when sampled by the EDC. Overall, except for Der f 1 and Mus m 1, significantly higher levels of all indoor allergens were collected on AAS filters than on the EDC, with mean values up to 11-fold greater for AAS samples than for EDCs (Fig 3, A, and Table III).

Four homes had frequent exposure to pets other than cats and dogs. One had a pet rabbit, 1 had pet guinea pigs, 1 had pet rats, and 1 had a horse on the property. The major allergens from these pets were all readily sampled by the AAS device, and in each home, the AAS device collected up to 11-fold more allergen compared with the EDC (Fig 3, B, and Table III).

In UK and US homes, the AAS device collected 13 food allergens from milk, egg, peanut, cashew, almond, walnut, hazelnut, mustard, sesame, and shrimp (Fig 3, C, and Table IV). Milk allergens Bos d 5 and Bos d 11 were found in almost every home sampled (89% and 100%, respectively). Egg allergen Gal d 2 was found in 89% of homes and airborne peanut, cashew, and sesame allergens were found in more than 50% of the homes sampled. In UK homes sampled with the EDC, 6 food allergens were collected, with Gal d 2 and Bos d 5 being collected most frequently (78% and 61%, respectively). In US homes, 11 food allergens were collected, although only Bos d 5, Bos d 11, and Gal

d 2 were found in more than 50% of the homes. Of 13 allergens detected, 8 of them were collected in significantly higher levels by AAS devices than by the EDCs, with mean values up to 45-fold greater for AAS devices.

Measurement of airborne endotoxin

Samples collected by the AAS devices over 7 days in the United Kingdom and the United States were analyzed for endotoxin content by Recombinant Factor C assay. Endotoxin was found in every home sampled (Fig 4, A). In UK homes with pets, there was significantly more endotoxin than in homes without pets ($P < .01$), with a mean of 236 EU/filter for homes with pets compared with 37 EU/filter for homes without pets. A similar trend was observed in the United States, with homes that had pets having almost 5-fold more endotoxin on average than homes without pets (183 EU/filter and 38 EU/filter, respectively), although this difference was not statistically significant ($P > .05$). The homes with the highest values of endotoxin owned a dog and a horse (917 EU/filter), and a cat, dog, and rabbit (879 EU/filter).

To assess the possibility of saturation of the AAS filters, longitudinal sampling was conducted in several UK homes. AAS devices were placed side by side, and the filters were removed at different time points (Fig 4, B, $n = 6$). The amount of endotoxin collected increased with the length of time sampled, with mean values of 36, 105, and 237 EU/filter after 1, 3, and 5 days of sampling, respectively. AAS devices were then run for 1, 7, 14, and 21 days (Fig 4, C, $n = 6$). The amount of endotoxin collected increased approximately 6-fold between 1 and 7 days, with mean endotoxin values of 75 and 446 EU/filter, respectively. Longer sampling periods of 14 and 21 days only resulted in small increases in the amount of endotoxin collected. At 14 days, the mean value was 595 EU/filter (a 1.3-fold increase from 7 days), and at 21 days, the mean value was 612 EU/filter (a 1.4-fold increase from 7 days). The time point at which saturation of the filters was reached was variable between each home sampled. Saturation was generally reached quicker if the

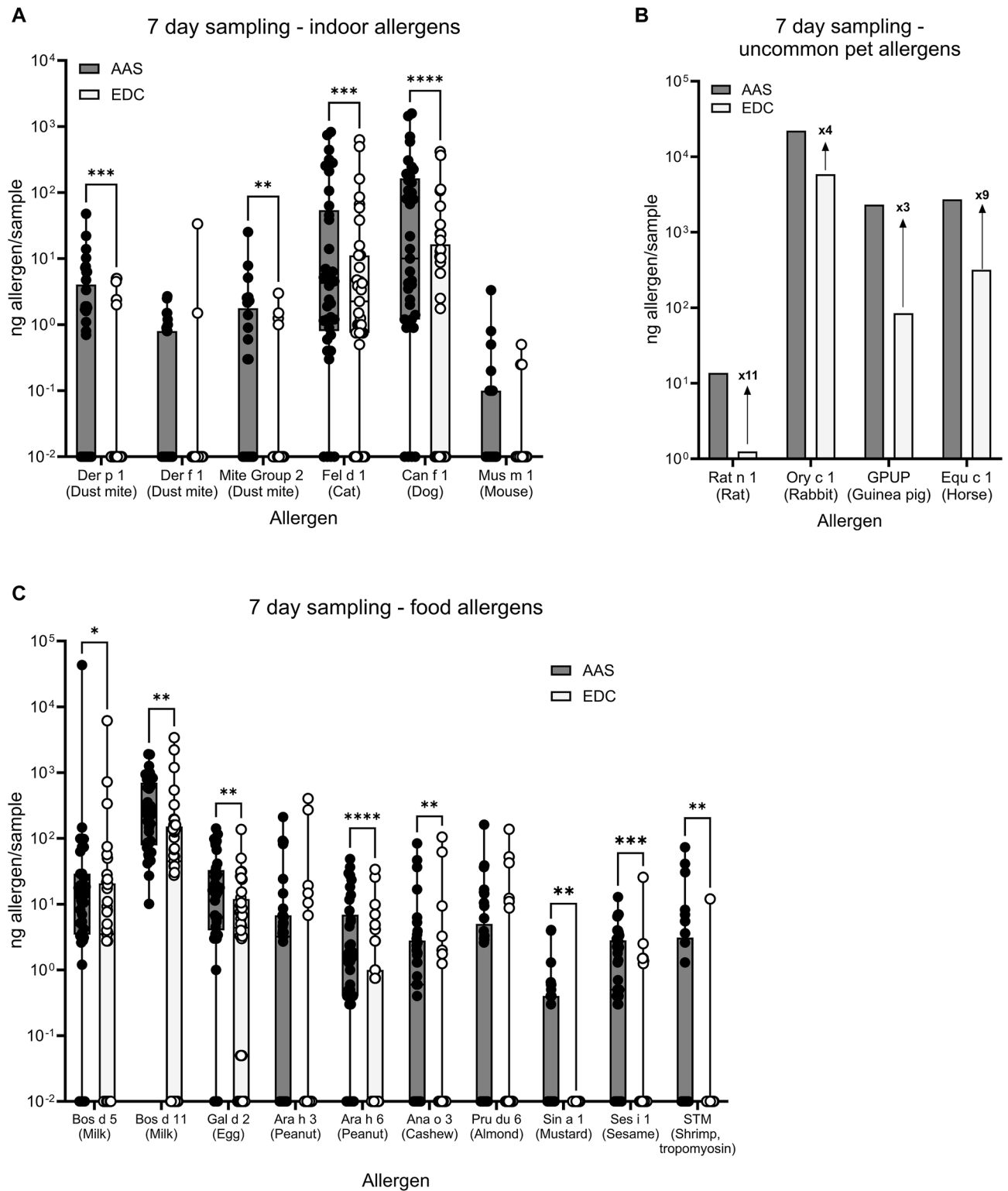


FIG 3. Measurement of aeroallergens after a 7-day sampling period. **A**, Indoor allergens captured by AAS devices (dark gray bars, solid symbols) and EDCs (light gray bars, open symbols) in UK and US homes ($n = 37$). **B**, Major pet allergens Ory c 3 (rabbit), guinea pig urinary protein (guinea pig), Rat n 1 (rat), and Equ c 1 (horse) captured by AAS devices (dark gray bars) and EDCs (light gray bars) in UK and US homes ($n = 1$). Numbers depict fold increase in measured allergen. **C**, Food allergens captured by AAS devices (dark gray bars, solid symbols) and EDCs (light gray bars, open symbols) in UK and US homes ($n = 37$). Gal d 1, Jug r 1, and Cor a 9 data not shown. All sampling was conducted over 7 days. Results expressed as ng allergen/sample. Arbitrary value of 0.01 was assigned for any sample below lower limit of detection. Multiple Wilcoxon matched pairs signed-rank tests, with a false-discovery rate approach was used to determine significance. $*P < .05$, $**P < .01$, $***P < .001$, $****P < .0001$.

TABLE III. Indoor allergens captured by AAS and EDCs after a 7-day sampling period

Location	Indoor allergens		Positivity rate		Average ng/sample	
	Source	Allergen	AAS	EDC	AAS	EDC
UK homes	Dust mite	Der p 1	78% (14 of 18)	22% (4 of 18)	5	0.78
		Der f 1	22% (4 of 18)	0% (0 of 18)	0.28	0.01*
		Mite Group 2	56% (10 of 18)	11% (2 of 18)	1.5	0.15
	Cat	Fel d 1	83% (15 of 18)	67% (12 of 18)	67	13
	Dog	Can f 1	89% (16 of 18)	28% (5 of 18)	137	10
	Mouse	Mus m 1	39% (7 of 18)	22% (4 of 18)	0.11	0.06
	Rabbit	Ory c 3	—	—	—	—
	Guinea pig	GPUP	1/1	1/1	2,729	318
	Rat	Rat n 1	—	—	—	—
	Horse	Equ c 1	—	—	—	—
US homes	Dust mite	Der p 1	21% (4 of 19)	5% (1 of 19)	3	0.27
		Der f 1	29% (5 of 19)	11% (2 of 19)	0.47	1.9
		Mite Group 2	29% (5 of 19)	11% (2 of 19)	1.6	0.23
	Cat	Fel d 1	95% (18 of 19)	95% (18 of 19)	116	73
	Dog	Can f 1	89% (17 of 19)	63% (12 of 19)	200	55
	Mouse	Mus m 1	29% (5 of 19)	11% (2 of 19)	0.20	0.05
	Rabbit	Ory c 3	1/1	1/1	22,122	5,873
	Guinea pig	GPUP	—	—	—	—
	Rat	Rat n 1	1/1	1/1	14	1.3
	Horse	Equ c 1	1/1	1/1	222	85

Positivity rate is expressed as a percentage, with the number of positive homes out of the total number sampled shown in parentheses. Average amount of allergen is expressed as nanogram of allergen per sample (ng/sample).

GPUP, Guinea pig urinary protein; LLOD, lower limit of detection.

*All results <LLOD were assigned an arbitrary value of 0.01.

starting amount of endotoxin was high (~100 EU/filter), compared with homes where the starting levels were much lower (<10 EU/filter).

DISCUSSION

The strong association between allergen exposure and allergic disease underscores the need for improved methods for measuring airborne allergens to better understand the dose-response relationship between exposure and disease activity. The goal of this pilot study was to develop a user-friendly air sampling device with high sampling efficiency and near-silent operation, suitable for routine air sampling in homes. The results demonstrate that the AAS efficiently captured a wide range of aeroallergens and airborne endotoxin by comparison with current IOM and EDC sampling devices. Measurement of indoor or food allergens in a single test using multiplex array technology enhanced the sensitivity of aeroallergen detection and was a key element of the exposure assessment.

The use of IOM samplers in the pharmaceutical industry has been beneficial in monitoring laboratory animal allergen exposure in vivaria and adjacent facilities.²⁰ Although IOM samplers are the criterion standard for measuring personal exposure, they have been used sparingly for domestic indoor and food allergen sampling studies, with limited success.^{16,31-33} In this pilot study, IOM samplers only collected Fel d 1 and Can f 1, and only from houses where cats or dogs resided, replicating previous findings.³¹ Assessment of airborne food allergens with IOM samplers has also been limited, with most studies only attempting to measure airborne peanut allergens, with partial success.^{31,34,35} In comparison, 2 major allergens from peanut were collected by the AAS device within 10 hours, together with 6 major allergens from milk, egg, cashew, walnut, and mustard. Exposures to milk and

egg aeroallergens were comparable to those of cat and dog allergens. In addition to the improved rate of allergen capture, the AAS device may be considered more user-friendly given the operating volume of 41 dB is considerably lower than that of the IOM pumps (SKC Sidekick), which operate at 62.5 dB unhooded and 55 dB when hooded.

Passive sampling of settled dust by EDCs has been used in several recent large studies, revealing their suitability for collection of indoor allergens and endotoxin.^{12,23} However, after sampling for extended periods, indoor allergens such as Der p 1 and Fel d 1 were not collected by the EDCs despite their presence in correlated vacuumed dust samples.^{10,36} This was confirmed in our side-by-side comparison over a 7-day sampling period, with Der p 1 being collected in 11 of 12 dust samples from UK homes, but only in 4 homes when sampled with an EDC (data not shown). The low positivity rate for EDCs may be explained by the very low levels of Der p 1 in the settled dust, with 8 of the 11 positive samples being less than or equal to 0.5 µg/g, potentially too low for the EDC to detect (data not shown). However, the AAS device demonstrated greater sensitivity than the EDC for all dust mite allergens, despite the low levels of these allergens in settled dust. A greater percentage of UK homes were positive for at least 1 dust mite allergen when compared with US homes. This disparity could reflect that unlike US homes, UK homes do not have heating, ventilation, and air conditioning systems. Heating, ventilation, and air conditioning systems tend to keep relative humidity levels at less than 50%, which is less conducive to dust mite growth. The AAS device also readily captured Fel d 1 and Can f 1 in almost every home, including those without pets. Fel d 1 and Can f 1 are carried on small airborne particles (~2-10 µm diameter) that remain in the air for long periods of time. Consequently, measuring airborne Fel d 1 and Can f 1 by the AAS device provides a more quantitative estimate of inhaled

TABLE IV. Food allergens captured by AAS and EDCs after a 7-day sampling period

Location	Food allergens		Positivity rate		Average ng/sample		
	Source	Allergen*	AAS	EDC	AAS	EDC	
UK homes	Milk	Bos d 5	94% (17 of 18)	61% (11 of 18)	2,437	354	
		Bos d 11	100% (18 of 18)	39% (7 of 18)	652	105	
	Egg	Gal d 1	22% (4 of 18)	0% (0 of 18)	12	0.01†	
		Gal d 2	94% (17 of 18)	78% (14 of 18)	36	7	
	Peanut	Ara h 3	50% (9 of 18)	11% (2 of 18)	8	16	
		Ara h 6	72% (13 of 18)	22% (4 of 18)	5	2	
	Cashew	Ana o 3	56% (10 of 18)	0% (0 of 18)	1.8	0.01†	
	Almond	Pru du 6	28% (5 of 18)	0% (0 of 18)	12	0.01†	
	Walnut	Jug r 1	22% (4 of 18)	6% (1 of 18)	1.1	0.23	
	Hazelnut	Cor a 9	22% (4 of 18)	0% (0 of 18)	0.82	0.01†	
	Mustard	Sin a 1	39% (7 of 18)	0% (0 of 18)	0.60	0.01†	
	Sesame	Ses i 1	61% (11 of 18)	0% (0 of 18)	1.2	0.01†	
	Shrimp	STM	39% (7 of 18)	0% (0 of 18)	6	0.01†	
	US homes	Milk	Bos d 5	84% (16 of 19)	58% (11 of 19)	20	63
			Bos d 11	100% (19 of 19)	84% (16 of 19)	222	399
Egg		Gal d 1	16% (3 of 19)	11% (2 of 19)	16	51	
		Gal d 2	84% (16 of 19)	63% (12 of 19)	22	17	
Peanut		Ara h 3	58% (11 of 19)	21% (4 of 19)	28	23	
		Ara h 6	95% (18 of 19)	47% (9 of 19)	9	3	
Cashew		Ana o 3	63% (12 of 19)	37% (7 of 19)	10	10	
Almond		Pru du 6	47% (9 of 19)	32% (6 of 19)	6	14	
Walnut		Jug r 1	42% (8 of 19)	26% (5 of 19)	8	11	
Hazelnut		Cor a 9	11% (2 of 19)	0% (0 of 19)	0.15	0.01†	
Mustard		Sin a 1	21% (4 of 19)	0% (0 of 19)	0.14	0.01†	
Sesame		Ses i 1	68% (13 of 19)	42% (8 of 19)	3	2	
Shrimp		STM	16% (3 of 19)	5% (1 of 19)	4	0.64	

Positivity rate is expressed as a percentage, with the number of positive homes out of the total number sampled shown in parentheses. Average amount of allergen is expressed as nanogram of allergen per sample (ng/sample).

LLOD, Lower limit of detection; STM, Shrimp tropomyosin.

*Also analyzed: Gly m 5—all results <LLOD.

†All results <LLOD were assigned an arbitrary value of 0.01.

exposure to these allergens compared with measuring them in settled or reservoir dust samples. Homes with pets harbor high levels of Fel d 1 and Can f 1, yet significant levels of these allergens have been reported in dwellings and settings without pets, such as schools, day-care centers, and even health care facilities.^{10,37,38} Sensitization to cats is more likely to develop in children exposed to moderate levels of Fel d 1 than in those exposed to high levels.^{39,40} Therefore, accurate measurement of these airborne pet allergens will be crucial in improving the efficacy of avoidance strategies aimed at reducing the risk of sensitization, and the number of allergy-related asthmatic episodes.^{15,41} This pilot study demonstrated that the AAS device could collect major allergens from other less common pets, namely, rabbits, guinea pigs, rats, and horses. These allergens are excreted in urine and are found on hair follicles and skin surfaces, which are present on airborne particles small enough to penetrate the lower respiratory tract.⁴² These allergen-carrying particles can be transported on clothes and shoes to animal-free environments including schools, workplaces, or “clean-rooms” in laboratory animal facilities. Because animal allergens are important sensitizing agents and a risk factor for asthma, the AAS device could be used for monitoring the presence of pet allergens and assist with implementation of avoidance or intervention controls.

It is estimated that 10% to 25% of allergic occupational asthma and rhinitis cases are due to food products, with animal and vegetable high-molecular-weight proteins derived from

aerosolized foods being a major causal agent.⁴³ Furthermore, although extremely rare, there have been reported incidences of anaphylactic reactions to airborne allergens. Few studies have measured multiple food allergens in homes or schools, and those that have relied on vacuumed dust or wipes.^{38,44,45} Results herein suggest that EDCs are not very efficient at capturing airborne food allergens, with differences between UK and US homes being observed. In comparison, the AAS device captured 13 major food allergens from UK and US homes, with up to 100% positivity rates. The one very high Bos d 5 result of approximately 45,000 ng/sample was due to consumption of daily powdered whey protein shakes by the occupant, leading to high amounts of aerosolized Bos d 5, without a correspondingly high Bos d 11 result (Fig 3, C). The rate at which airborne food allergens were collected from UK and US homes was remarkably similar, emphasizing the potential ability of the AAS device to provide a standardizable sampling method for food allergen exposure worldwide. It has been hypothesized that nonoral routes of sensitization, that is, through the skin or the respiratory mucosa, could lead to the development of food allergy.⁴⁶⁻⁴⁸ Given the limited treatment options for food allergies, measurement of airborne food allergens by the AAS device could play an important role in investigating environmental exposures as a cause of food allergy and in developing potential mitigation strategies. The AAS device could be used to monitor airborne food allergens in bakeries and food processing plants where potentially high

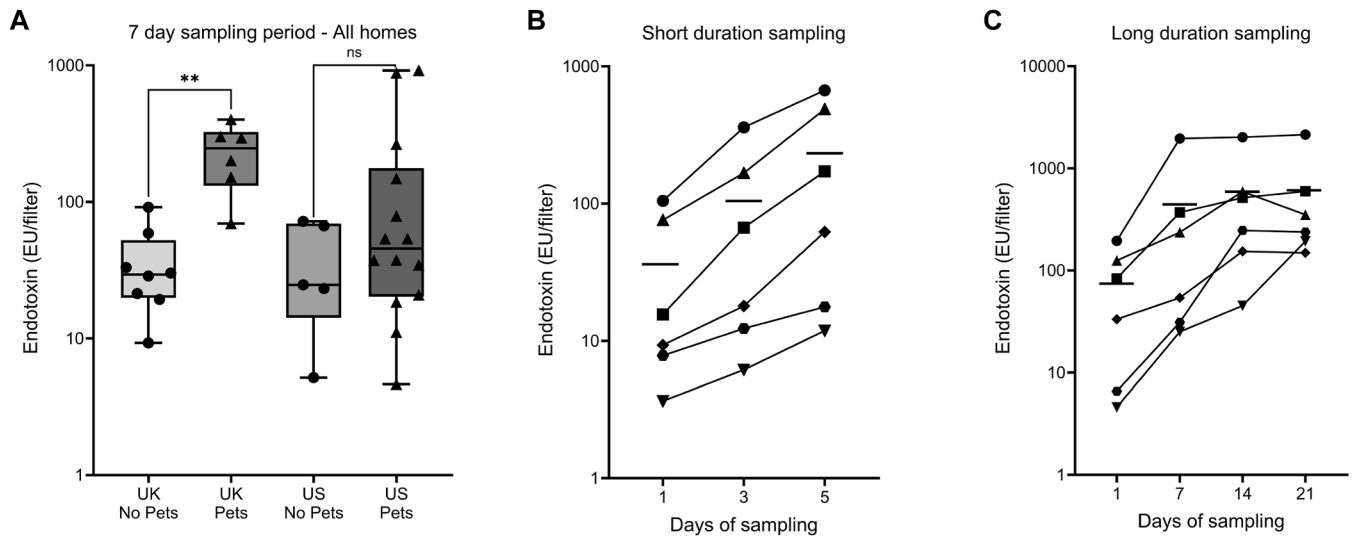


FIG 4. Comparison of airborne endotoxin exposures in UK and US homes using the AAS. **A**, Endotoxin captured by AAS devices in UK and US homes after 7 days of sampling. Samples are divided into homes without pets (circles) and homes with pets (triangles). Mann-Whitney *U* test was used to determine significance. *NS*, Not significant. *******P* < .01. **B**, Endotoxin captured by AAS devices in UK homes after 1, 3, and 5 days of sampling. Individual homes are depicted by different symbols, with mean of all samples at each time point shown by black solid line. **C**, Endotoxin captured by AAS devices in UK homes after 1, 7, 14, and 21 days of sampling. Individual homes are depicted by different symbols, with mean of all samples at each time point shown by black solid line. All results expressed as endotoxin units per filter as determined by Recombinant Factor C assay.

exposure and inadequate controls may pose a risk, as well as in schools, offices, and health care settings, where exposure to food allergens could be an unaccounted-for source of sensitization.³⁸

Airborne endotoxin exposure in indoor environments has been measured by numerous methods, with little consensus on standardization of sampling techniques, duration of sampling, extraction methods, and analytical testing. Results presented here demonstrate that the AAS device could provide a useful alternative for the measurement of airborne endotoxin, with endotoxin found in every home in the United Kingdom and the United States after 7 days of sampling. Sampling times for environmental endotoxin can vary from minutes to weeks, depending on the sampling method deployed.²⁶ Preliminary data presented here demonstrate that the AAS device can collect endotoxin in homes from as little as 24 hours, with increased levels measured at 3 and 5 days. In homes, sampling beyond 7 days may lead to filter saturation, particularly in homes with higher initial levels of endotoxin. Allergen levels were also measured in the short-duration longitudinal samples. Although only a small number of houses were sampled, the results showed that more abundant allergens such as *Bos d 5* showed high positivity rates at both 1 and 3 days of sampling (83%), reaching 100% after 5 days. However, less abundant allergens such as *Der p 1* and *Ara h 3* showed increased positivity rates with increased sampling times. After 1 day of sampling, there was a 33% positivity rate for both allergens, after 3 days of sampling, 50% positivity for *Der p 1* and 83% positivity for *Ara h 3*, and after 5 days of sampling, there was an 83% and 100% positivity, respectively (see this article's Results section and [Table E2](#) in the Online Repository at www.jaci-global.org). Given the highly efficient capture of both allergens and endotoxin in homes at 5

and 7 days, sampling for 5 days would be ideal for measuring occupational exposure during a working week or childhood exposure in schools, especially given the near-silent operating level. Sampling for 7 days could be recommended for exposure in homes, where a full week of sampling may be important, given possible differences between weekend and weekday exposures.

A limitation of this study was the selection of homes that were chosen for sampling. Homes sampled were those of employees of InBio and their family members. They did not include a diverse range of dwellings, nor did the occupants have allergies or chronic asthma. For further validation of the AAS device, large population studies including patients with allergies, asthma, and other chronic respiratory diseases would be needed. Additional validations should also expand the short-duration sampling to a larger cohort to further investigate the ideal sampling duration for both allergens and endotoxin. It may also be beneficial for future studies to compare the ability of the AAS device to capture allergens at different positions within the room. All sampling in this pilot study was performed with the AAS device placed on a table or a shelf at a minimum height of 1 m. If the AAS device was shown to collect allergens at the same rate whether placed at table height, shoulder height, or closer to ground level, this would improve the user-friendliness of the device and aid in the design of future assessments of specific environmental exposure to subjects. Given the high flow rate and large sampling area of the AAS device, there may be a bias toward the collection of smaller particles compared with the IOM sampler or the EDC, which may lead to an underestimate of allergens carried on larger particles. This is likely to explain the higher average amount of *Fel d 1* and *Can f 1* collected by the IOM sampler compared with the AAS device ([Table II](#)). However, this limitation is offset by the benefit

of sampling a large volume of air and consequently an increased ability to capture particles more likely to be respirable, leading to higher positivity rates of allergen capture than both IOM sampling and EDC passive sampling.

Conclusion

Monitoring environmental allergen exposure to improve the effectiveness of intervention strategies requires efficient, standardizable, and user-friendly methods. Given the complex aerodynamic properties of the particles that airborne allergens are carried on, this should include active measurement of airborne exposure in conjunction with assessment of allergen content in settled or reservoir dust. Here, we have demonstrated how an efficient ambient air sampling device coupled with specific immunoassays provides a novel solution. Next steps to further validate the AAS device for environmental exposure assessments of airborne allergens and endotoxin would be for its use in much larger exposure studies, both in homes and in workplaces, and potentially in clinical trials. Given the high flow rate and efficient capture of biologically relevant particles, the AAS device may also be suitable for the collection of airborne bacteria, fungi, and viruses that are associated with the development and exacerbation of respiratory diseases.

DISCLOSURE STATEMENT

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors and was solely funded by InBio.

Disclosure of potential conflict of interest: M. A. Oliver, R. T. Meredith, M. D. Bermingham, E. K. Sturt, E. A. Heath, S. C. Filep, A. Kuklinska-Pijanka, R. A. R. Yarham, H. Mills, and M. D. Chapman are employees of InBio. M. D. Chapman has a financial interest in InBio and is a founder of the company.

We are grateful to Angharad Cullinane for technical support in developing early prototypes of the AAS, and to Meagan Cook for graphic design. We also thank the GX Group for their collaboration in the design, engineering, and assembly of the AAS.

Key messages

- Aeroallergens from dust mites, pets, mice, and multiple foods including milk, egg, peanut, tree nuts, sesame, mustard, and shrimp were collected by the AAS device when sampling homes in the United Kingdom and the United States.
- Airborne endotoxin was collected from every home sampled.
- The AAS device could standardize the monitoring of airborne allergen and endotoxin exposure.

REFERENCES

1. Wahn U, Lau S, Bergmann R, Kulig M, Forster J, Bergmann K, et al. Indoor allergen exposure is a risk factor for sensitization during the first three years of life. *J Allergy Clin Immunol* 1997;99:763-9.
2. Salo PM, Arbes SJ Jr, Crockett PW, Thorne PS, Cohn RD, Zeldin DC. Exposure to multiple indoor allergens in US homes and its relationship to asthma. *J Allergy Clin Immunol* 2008;121:678-84.e2.
3. Grant TL, Wood RA, Chapman MD. Indoor environmental exposures and their relationship to allergic diseases. *J Allergy Clin Immunol Pract* 2023;11:2963-70.

4. Raulf M, Buters J, Chapman M, Cecchi L, de Blay F, Doekes G, et al. Monitoring of occupational and environmental aeroallergens—EAACI Position Paper. Concerted action of the EAACI IG Occupational Allergy and Aerobiology & Air Pollution. *Allergy* 2014;69:1280-99.
5. Gold DR, Adamkiewicz G, Arshad SH, Celedon JC, Chapman MD, Chew GL, et al. NIAID, NIEHS, NHLBI, and MCAN Workshop Report: the indoor environment and childhood asthma—implications for home environmental intervention in asthma prevention and management. *J Allergy Clin Immunol* 2017;140:933-49.
6. Chapman MD, Custovic A, Clare EN, Mills TH. Molecular exposure: systemic approaches, clinical significance, and harmonisation. 2.0. In: Ö. Kalayci, *Molecular Allergology User's Guide 2.0*, 2023. European Academy of Allergy and Clinical Immunology, Pediatric Allergy and Immunology 2023;155-68.
7. Sandel M, Murphy JS, Dixon SL, Adgate JL, Chew GL, Dorevitch S, et al. A side-by-side comparison of three allergen sampling methods in settled house dust. *J Expo Sci Environ Epidemiol* 2014;24:650-6.
8. Platts-Mills TA, Vervloet D, Thomas WR, Aalberse RC, Chapman MD. Indoor allergens and asthma: report of the Third International Workshop. *J Allergy Clin Immunol* 1997;100:S2-24.
9. Peterson EL, Ownby DR, Kallenbach L, Johnson CC. Evaluation of air and dust sampling schemes for Fel d 1, Der f 1, and Der p 1 allergens in homes in the Detroit area. *J Allergy Clin Immunol* 1999;104:348-55.
10. Custovic A, Simpson B, Simpson A, Hallam C, Craven M, Woodcock A. Relationship between mite, cat, and dog allergens in reservoir dust and ambient air. *Allergy* 1999;54:612-6.
11. Tovey ER, Mitakakis TZ, Sercombe JK, Vanlaar CH, Marks GB. Four methods of sampling for dust mite allergen: differences in 'dust'. *Allergy* 2003;58:790-4.
12. Sander I, Lotz A, Neumann HD, Czibor C, Zahradnik E, Raulf M. Reliability and correlation between indoor allergen concentrations from vacuumed surface samples and electrostatic dust collectors. *Ann Work Expo Health* 2020;64:165-74.
13. de Blay F, Heymann PW, Chapman MD, Platts-Mills TA. Airborne dust mite allergens: comparison of group II allergens with group I mite allergen and cat-allergen Fel d 1. *J Allergy Clin Immunol* 1991;88:919-26.
14. Sakaguchi M, Inouye S, Irie T, Miyazawa H, Watanabe M, Yasueda H, et al. Airborne cat (Fel d 1), dog (Can f 1), and mite (Der I and Der II) allergen levels in the homes of Japan. *J Allergy Clin Immunol* 1993;92:797-802.
15. Custovic A, Green R, Fletcher A, Smith A, Pickering CA, Chapman MD, et al. Aerodynamic properties of the major dog allergen Can f 1: distribution in homes, concentration, and particle size of allergen in the air. *Am J Respir Crit Care Med* 1997;155:94-8.
16. Custovic A, Simpson A, Pahdi H, Green RM, Chapman MD, Woodcock A. Distribution, aerodynamic characteristics, and removal of the major cat allergen Fel d 1 in British homes. *Thorax* 1998;53:33-8.
17. Custovic A, Woodcock H, Craven M, Hassall R, Hadley E, Simpson A, et al. Dust mite allergens are carried on not only large particles. *Pediatr Allergy Immunol* 1999;10:258-60.
18. Maya-Manzano JM, Pusch G, Ebner von Eschenbach C, Bartusel E, Belzner T, Karg E, et al. Effect of air filtration on house dust mite, cat and dog allergens and particulate matter in homes. *Clin Transl Allergy* 2022;12:e12137.
19. Feistenaue S, Sander I, Schmidt J, Zahradnik E, Raulf M, Briemeier M. Influence of 5 different caging types and the use of cage-changing stations on mouse allergen exposure. *J Am Assoc Lab Anim Sci* 2014;53:356-63.
20. Westall L, Graham IR, Bussell J. A risk-based approach to reducing exposure of staff to laboratory animal allergens. *Lab Anim (NY)* 2015;44:32-8.
21. Straumfors A, Eduard W, Andresen K, Sjaastad AK. Predictors for increased and reduced rat and mouse allergen exposure in laboratory animal facilities. *Ann Work Expo Health* 2018;62:953-65.
22. Grant T, Rule AM, Koehler K, Wood RA, Matsui EC. Sampling devices for indoor allergen exposure: pros and cons. *Curr Allergy Asthma Rep* 2019;19:9.
23. Sander I, Lotz A, Liebers V, Zahradnik E, Sauke-Gensow U, Petersen J, et al. Comparing the concentration levels of allergens and endotoxins in employees' homes and offices. *Int Arch Occup Environ Health* 2022;95:573-88.
24. Reed CE, Milton DK. Endotoxin-stimulated innate immunity: a contributing factor for asthma. *J Allergy Clin Immunol* 2001;108:157-66.
25. Thorne PS, Mendy A, Metwali N, Salo P, Co C, Jaramillo R, et al. Endotoxin exposure: predictors and prevalence of associated asthma outcomes in the United States. *Am J Respir Crit Care Med* 2015;192:1287-97.
26. Duquenne P, Marchand G, Duchaine C. Measurement of endotoxins in bioaerosols at workplace: a critical review of literature and a standardization issue. *Ann Occup Hyg* 2013;57:137-72.
27. Earle CD, King EM, Tsay A, Pittman K, Saric B, Vailes L, et al. High-throughput fluorescent multiplex array for indoor allergen exposure assessment. *J Allergy Clin Immunol* 2007;119:428-33.
28. King EM, Filep S, Smith B, Platts-Mills T, Hamilton RG, Schmechel D, et al. A multi-center ring trial of allergen analysis using fluorescent multiplex array technology. *J Immunol Methods* 2013;387:89-95.

29. Filep SC, Reid Black K, Smith BRE, Block DS, Kuklinska-Pijanka A, Bermingham M, et al. Simultaneous quantification of specific food allergen proteins using a fluorescent multiplex array. *Food Chem* 2022;389:132986.
30. Filep S, Chapman MD. Doses of specific allergens in early introduction foods for prevention of food allergy. *J Allergy Clin Immunol Pract* 2022;10:150-8.e3.
31. Tulum L, Deag Z, Brown M, Furniss A, Meech L, Lalljie A, et al. Airborne protein concentration: a key metric for type 1 allergy risk assessment—in home measurement challenges and considerations. *Clin Transl Allergy* 2018;8:10.
32. Tovey ER, Willenborg CM, Crisafulli DA, Rimmer J, Marks GB. Most personal exposure to house dust mite aeroallergen occurs during the day. *PLoS One* 2013;8:e69900.
33. Tovey ER, Liu-Brennan D, Garden FL, Oliver BG, Perzanowski MS, Marks GB. Time-based measurement of personal mite allergen bioaerosol exposure over 24 hour periods. *PLoS One* 2016;11:e0153414.
34. Perry TT, Conover-Walker MK, Pomes A, Chapman MD, Wood RA. Distribution of peanut allergen in the environment. *J Allergy Clin Immunol* 2004;113:973-6.
35. Brough HA, Makinson K, Penagos M, Maleki SJ, Cheng H, Douiri A, et al. Distribution of peanut protein in the home environment. *J Allergy Clin Immunol* 2013;132:623-9.
36. Kristono GA, Shorter C, Pierse N, Crane J, Siebers R. Endotoxin, cat, and house dust mite allergens in electrostatic cloths and bedroom dust. *J Occup Environ Hyg* 2019;16:89-96.
37. Sander I, Lotz A, Neumann HD, Czibor C, Flagge A, Zahradnik E, et al. Indoor allergen levels in settled airborne dust are higher in day-care centers than at home. *Allergy* 2018;73:1263-75.
38. Leal M, Paciencia I, Farraia M, Cavaleiro Rufo J, Castro Mendes F, Delgado L, et al. Airborne food allergen and aeroallergen levels in health care settings: an unaccounted for but potentially relevant source of exposure? *J Investig Allergol Clin Immunol* 2021;31:426-32.
39. Platts-Mills T, Vaughan J, Squillace S, Woodfolk J, Sporik R. Sensitisation, asthma, and a modified Th2 response in children exposed to cat allergen: a population-based cross-sectional study. *Lancet* 2001;357:752-6.
40. Custovic A, Hallam CL, Simpson BM, Craven M, Simpson A, Woodcock A. Decreased prevalence of sensitization to cats with high exposure to cat allergen. *J Allergy Clin Immunol* 2001;108:537-9.
41. Liccardi G, D'Amato G, Russo M, Canonica GW, D'Amato L, De Martino M, et al. Focus on cat allergen (Fel d 1): immunological and aerodynamic characteristics, modality of airway sensitization and avoidance strategies. *Int Arch Allergy Immunol* 2003;132:1-12.
42. Curin M, Hilger C. Allergy to pets and new allergies to uncommon pets. *Allergol Select* 2017;1:214-21.
43. Jeebhay MF, Moscato G, Bang BE, Folletti I, Lipinska-Ojrzanowska A, Lopata AL, et al. Food processing and occupational respiratory allergy—an EAACI position paper. *Allergy* 2019;74:1852-71.
44. Maciag MC, Sheehan WJ, Bartnikas LM, Lai PS, Petty CR, Filep S, et al. Detection of food allergens in school and home environments of elementary students. *J Allergy Clin Immunol Pract* 2021;9:3735-43.
45. Bertelsen RJ, Faeste CK, Granum B, Egaas E, London SJ, Carlsen KH, et al. Food allergens in mattress dust in Norwegian homes - a potentially important source of allergen exposure. *Clin Exp Allergy* 2014;44:142-9.
46. Berin MC, Sampson HA. Mucosal immunology of food allergy. *Curr Biol* 2013;23:R389-400.
47. Brough HA, Nadeau KC, Sindher SB, Alkotob SS, Chan S, Bahnson HT, et al. Epicutaneous sensitization in the development of food allergy: what is the evidence and how can this be prevented? *Allergy* 2020;75:2185-205.
48. Kulis MD, Smeekens JM, Immormino RM, Moran TP. The airway as a route of sensitization to peanut: an update to the dual allergen exposure hypothesis. *J Allergy Clin Immunol* 2021;148:689-93.