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ALLERGENS (R. K. BUSH & S. VIETHS, SECTION EDITORS)

# Sampling Devices for Indoor Allergen Exposure: Pros and Cons

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**Abstract**

**Purpose of Review** To review current indoor allergen sampling devices, including devices to measure allergen in reservoir and airborne dust, and personal sampling devices, with attention to sampling rationale and major indoor allergen size and characteristics.

**Recent Findings** While reservoir dust vacuuming samples and airborne dust volumetric air sampling remain popular techniques, recent literature describes sampling using furnace filters and ion-charging devices, both which help to eliminate the need for trained staff; however, variable correlation with reservoir dust and volumetric air sampling has been described. Personal sampling devices include intra-nasal samples and personal volumetric air samples. While these devices may offer better estimates of breathable allergens, they are worn for short periods of time and can be cumbersome.

**Summary** Reservoir dust sampling is inexpensive and is possible for families to perform. Airborne dust sampling can be more expensive and may better quantify cat, dog, and mouse allergen exposure. Personal sampling devices may offer a better representation of breathable air.

**Keywords** Indoor allergen exposure · Indoor allergen sampling · Vacuum allergen sampling · Allergen in settled dust · Airborne allergen sampling · Personal allergen samplers

## Introduction

Indoor allergen exposure is associated with allergic rhinitis and asthma morbidity, including medication use, symptom days, days of missed work or school, unscheduled doctors' visits, urgent care/emergency room visits, and hospitalizations [1–7]. More recently, indoor allergen exposure has been linked to asthma controller medication treatment step and asthma severity [8]. Large studies have reported associations between reduction of indoor allergen exposure and improvement in asthma symptoms and health care utilization [9, 10].

In addition to research applications, national guidelines and clinical practice parameters recommend environmental exposure assessment and allergen reduction for the clinical care of patients with allergic rhinitis and asthma, and there is a recent movement for health care payers and insurance to cover home exposure assessment and remediation as an important component of asthma control [11–15]. Therefore, there is great interest in environmental sampling of indoor allergens in order to assess exposure. Here, we review current indoor allergen sampling devices.

## Rationale for Sampling and Why It Is Important to Estimate Exposure

In measuring indoor allergen exposure, the goal for rhinitis and asthma is to quantify the indoor allergens that penetrate the upper and lower airways. For example, in asthma, we are interested specifically in understanding the quantity of the allergen of interest that penetrates the conducting airways. An ideal sensor would sample the allergen-containing particles that reach the bronchi and bronchioles and record allergen concentration at high temporal resolution. However, in the absence of such a device, we rely on sometimes rather crude

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approaches for estimating respiratory tract indoor allergen exposure.

Indoor allergen exposure is important in a variety of biomedical settings. Clinically, we are interested in a patient's indoor allergen exposure and the reduction of that patient's exposure for the management of his/her allergic rhinitis and asthma [6, 7, 9, 10]. In occupational health, we are interested in the role of indoor allergen exposure and its role in occupational allergic disease, such as occupational asthma, in order to inform management of exposure and the worker's allergic disease [16, 17]. On a larger public health scale, we are interested in how indoor allergen exposure at the population level mitigates or confers allergic disease risk and contributes to a population's burden of allergic rhinitis and asthma [1–4, 7, 18–20]. Lastly, we are interested in how indoor allergen exposure influences cellular and molecular processes in order to better understand mechanisms of allergic disease and identify pathways to target in developing therapeutic agents [21–24].

## General Approaches to Sampling

In general, indoor allergen exposure sampling can be divided into two main approaches: measurement of indoor allergens in dust reservoirs and measurement of indoor allergens suspended in the air. Measurement of indoor allergens in air can further be divided into area samples (the sampler is located in a specific room or area) and personal samples (the sampler is carried by the individual).

## Particle Size and Characteristics of Major Indoor Allergens

Allergen-containing particles contain allergen and non-allergenic substances [25•]. Understanding the particle size characteristics of allergens can help determine which indoor allergens penetrate specific regions of the respiratory tract, and which sampling strategy is best for quantifying airway exposure. For the purposes of this review focused on indoor allergens, small particles are considered those ≤ 10 μm in diameter and tend to deposit deeper into the respiratory tract, whereas large particles are considered > 10 μm in diameter and tend to deposit in the upper airways. The major indoor allergens that have been associated with allergic rhinitis and asthma include cat, dog, dust mite, cockroach, mouse, and fungi ("molds"). Outdoor allergens, such as pollens, and other pollutants may intrude the indoor space, also contributing to morbidity. However, here, we will focus on exposure assessment methods for animal and pest allergens.

*Cat:* Cats are among the most common furry pets in American homes, with ~38% of homes reporting ownership in one survey [26]. The major cat allergen, Fel d 1, tends to be associated with small particles and is present in cat skin, hair follicles, sebaceous, anal, and salivary glands [25•, 27••]. Allergic sensitization to cat is common among the general population and patients with asthma. In homes, Fel d 1 is found on upholstered furniture, bedding, carpets, and clothing and can remain airborne for extended periods of time [28]. Fel d 1 is readily transferred via clothing to homes without cats, most commonly on upholstered living room furniture, and has been found in public places such as schools, daycares, movie theaters, public transit and airplane seats, and workplaces [28–33].

*Dog:* Dogs are the most common furry American household pet, with ~48% of homes reporting ownership, and with allergic sensitization being common [26]. Can f 1, the major dog allergen, tends to be carried on small particles and is found in dog hair, dander, and saliva [27••, 34]. It is found on upholstered furniture, carpeting, and beds, and in homes without dogs [34]. Like Fel d 1, Can f 1 also remains airborne for long periods of time and is transferred via clothing to public places such as schools, daycares, office buildings, and public transport [30, 35, 36].

*Dust mite:* Dust mite allergens (Der f 1 and Der p 1) tend to be associated with large-size particles that settle rapidly [37]. Dust mite concentrations correlate with humidity, with greater than 55% humidity being associated with higher dust mite allergen levels [37]. In homes, Der f 1 and Der p 1 are found in carpeting, upholstered furniture, bedding, mattresses, and soft toys. Der f 1 and Der p 1 are also found in schools, daycares, public transport, offices, health care settings, and on clothing [29, 30, 32, 33, 38].

*Cockroach:* The major German cockroach allergens (Bla g 1 and Bla g 2) are the most prominent cockroach allergens associated with allergic disease, and they tend to be associated with large particles [39]. Exposure is commonly associated with urban, low-income populations, but cockroach allergens are also present in suburban and rural homes and schools. Cockroach allergens are more commonly found in settled dust than in airborne samples. High concentrations are often found near food preparation and storage areas, such as kitchens or cafeterias.

*Mouse:* Mus m 1, the major mouse allergen, is excreted in mouse urine and the large majority tends to be found on small particles, so that it remains airborne for extended periods of time [27••]. Like cockroach, mouse allergen is primarily associated with low-income, urban homes and schools, where it has been reported in up to 100% of homes and schools, but it is also commonly found in suburban homes and schools, albeit at lower concentrations [40–42].

*Fungi (molds)*: Common fungi implicated in allergic disease include *Penicillium*, *Aspergillus, Alternaria*, and *Cladosporium* [25•]. These fungi are commonly found in damp areas, areas with water damage, and on plants and soil [25•, 43]. Outdoor fungi can enter homes through open windows/doors or on clothing or pets. Fungi may influence the immune system and airways by multiple mechanisms, and

there are multiple exposure assessment methods that measure a range of fungal attributes [44–46]. Available methods quantify viable and non-viable spores, fungal wall components, fungal allergens, and fungal communities using nucleic acid-based methods [45, 46]. Fungal exposure assessment is therefore quite complex and beyond the scope of this review.

## Indoor Allergen Sampling Devices (Table 1)

### Reservoir Dust

#### Vacuum Sampling

Handheld vacuum cleaners are used to collect dust accumulated on the floors, beds, and upholstered and non-upholstered surfaces. The dust sample may be collected on filters, using woven fabric, or in nylon bags. Inlets attach to the vacuum nozzle and can select for particles using a pre-filter [47•]. Standard surfaces to vacuum include living room and bedroom carpeting, upholstered living room furniture, kitchen flooring, bed, and bedding. While there is no universal protocol for sampling area or duration, it is important to select a specific study protocol that is used for the entirety of the study. Examples of duration of living room and bedroom floor vacuuming include 2 min of sampling per $m^2$, 1 min of sample per $m^2$, with the sampling area either comprising of 1 adjacent 1-$m^2$ or 4 nonadjacent 0.25-$m^2$ areas [47•, 48, 49]. Kitchen flooring may be vacuumed in its entirety for 2 min, and upholstered furniture can be vacuumed for 2 min per piece of furniture [50]. Bedding may be pulled back to reveal a fitted sheet or sleeping surface, which is subsequently vacuumed for 1 min [51]. A more comprehensive approach is to vacuum the top half of the bed, the area where the head to waist would normally be located, sampling the comforter, blankets, top/bottom sheets, mattress, and both sides of any pillows, for a total of 5 min. The amount of dust collected depends on vacuum flow rate, the amount of dust present in the selected area, and the duration and size of the area sampled. High-flow vacuuming is typically at a flow rate of ~ 600 L/min; vacuums with lower flow rates include the American Industrial Hygiene Association protocol, which use a flow rate of 171 L/min. Even though lower flow rates have been associated with a higher percentage of samples with insufficient dust collection for later analysis, most studies use the lower-flow commercial vacuums with a high rate of sufficient samples [51]. Protein is then extracted from the dust samples and the allergen quantified by immunoassay. Total recoverable allergen in absolute mass may be difficult to compare across studies given the varied sampling techniques; however, allergen quantity is typically expressed as mass of allergen per mass of dust collected (i.e., μg/g), which is more comparable across studies. Allergen quantity can also be expressed as a "load," which is expressed as μg/$m^2$ of area sampled.

*Pros:* Vacuum dust sampling is inexpensive, fast, and easily obtained. Samples may be collected from multiple surfaces in the same visit. It is possible to train families to perform their own collection of reservoir dust with good correlation to reservoir dust collected by trained technicians [52•]. In addition, grab samples from the home's vacuum bag have shown good correlation with collected reservoir dust [53•]. Reservoir dust sampling has been shown to be better than air sampling for measuring dust mite and cockroach allergens, as these allergens are primarily found on large particles, which quickly settle, and are less readily airborne than allergens found primarily on smaller particles such as cat, dog, and mouse allergens.

*Cons*: Vacuum dust sampling is less representative of allergen airway exposure than air sampling techniques, as there are poor to moderate correlations between settled dust and airborne allergen concentrations, although the strength of the correlation depends on the specific allergen [54]. There can be variability in the methods used to collect the dust samples, as there may be differences in the locations that are sampled, the size of the area sampled, the duration of vacuuming, and the vacuum flow rate.

#### Settling Dust

Settling dust sampling devices are intended to capture allergen-bearing particles as they settle on surfaces. The three most utilized are Petri dishes, A-books, and electrostatic dust collectors. Petri dishes (also called settling plates) are circular plates (typically 10–15 cm in diameter), pretreated to block protein binding, which are left open and undisturbed for a designated period of time, such as 7 days [47]. Dishes are then scraped, suspended in eluate, and allergen content is measured in the eluate by immunoassay [47]. Allergen concentration is reported in total ng or μg of allergen or ng/$m^2$/day.

Adhesive-membrane systems are small booklets which utilize a 5 × 5-cm piece of adhesive tape on one half and a 5 × 5-cm polyvinylidene difluoride membrane on the other half. The booklets are positioned up and open and are left undisturbed for, typically, 7 days, after which the booklet is closed and the allergen particles are retained between the adhesive tape and the membrane [47]. The membranes are then immunostained and allergen is reported in allergenic particles/$m^2$/day.

Electrostatic dust collectors (EDCs) utilize 2 or 4 electrostatic cloths in plastic folders and can be left open in homes or schools for up to 28 days [55]. Allergen protein is extracted from the cloth and quantified using allergen assays. Allergen concentrations are reported in ng/$m^2$/week. Electrostatic cloths can also be used to wipe surfaces.

*Pros*: Settling dust devices are inexpensive, easy to deploy, and eliminate the need for a vacuum and electricity. Devices

**Table 1** Characteristics of indoor allergen sampling devices

| Method | Recommendations and considerations | Pros | Cons |
|---|---|---|---|
| Reservoir dust | | | |
| *Vacuum sampling* | • Recommended for assessment of chronic exposure to all of the indoor allergens<br>• Less representative of airway exposure compared to airborne dust<br>• Better measure of chronic than acute exposure | • Easy to deploy<br>• Lay people can be trained to collect own samples.<br>• Samples can be collected from multiple surfaces.<br>• Low cost[a] | • Collection techniques may be variable, resulting in variability in samples collected.<br>• Temporal scale of exposure imprecise |
| *Settling dust* | • Recommended for assessment of chronic exposure to all of the indoor allergens<br>• Less representative of airway exposure compared to airborne dust | • Easy to deploy<br>• Lay people can be trained to collect own samples.<br>• Suitable for large-scale studies<br>• Low cost[a] | • Samplers must be left out for several days to weeks. |
| Airborne dust | | | |
| *Area volumetric air sampling* | • Recommended for assessment of acute or chronic exposure to furry animal allergens<br>• Better for furry animal allergens than cockroach and dust mite allergens, which tend to be on larger particles, so are more difficult to measure in air samples<br>• Better representation airway exposure than reservoir dust<br>• Can select for particle sizes that penetrate the respiratory tract | • Allows for particle size selection<br>• Standardized equipment and methods allow for cross-study comparisons. | • Need for equipment calibration<br>• Requires trained staff<br>• Moderate to high cost[a] |
| *Furnace filter* | • Recommended for assessment of chronic exposure to furry animal allergens<br>• Better for furry animal allergens than cockroach and dust mite<br>• Possible representation of breathable air in home during time period when filter was in place | • No extra equipment needed if home has central HVAC system<br>• Lay people can be trained to collect own samples<br>• Low cost[a] | • Filters and HVAC systems vary across homes.<br>• Some homes do not have central HVAC systems.<br>• Vacuuming of filter may not collect representative dust sample from filter. |
| *Ionic sampling* | • May be useful for assessment of acute or chronic exposure to indoor allergens<br>• Better collection of larger particles than smaller particles<br>• Potentially better representation of airway exposure than reservoir dust | • Lay people can be trained to collect own samples.<br>• More sensitive than volumetric sampling<br>• Quieter operation than volumetric samplers<br>• More efficient particle collection than volumetric samplers<br>• Moderate to high cost[a] | • Allergen concentrations measured much lower than when measured by volumetric sampling<br>• Less efficient collection of smaller than larger particles |
| Personal samplers | | | |
| *Intra-nasal samplers* | • Recommended for assessment of short-term (hours) acute exposure to allergens<br>• Can be used for all allergens, but better for smaller particles<br>• Better representation of airway exposure than reservoir dust sampling<br>• Potentially better representation of acute airway exposure than other airborne dust sampling methods | • Easy to use<br>• Captures particles entering the airway<br>• Moderate cost[a] | • May be cumbersome to use for longer than minutes-hours<br>• Best when individual only breathes nasally since it does not capture exposure via mouth breathing<br>• Assays for allergen quantification more cumbersome than assays for other sampling methods |
| *Personal volumetric air samplers* | • Recommended for assessment of acute exposure to furry animal allergens<br>• Better representation of airway exposure than reservoir dust sampling<br>• Better representation of personal exposure than stationary volumetric sampling since it moves with the individual<br>• Short-term measurement could be used as surrogate for chronic exposure. | • Can estimate hourly, daily personal exposure<br>• Allows for particle size selection<br>• Standardized equipment and methods allow for cross-study comparisons. | • Devices are noisy and cumbersome to wear.<br>• Need for equipment calibration<br>• Requires trained staff<br>• Moderate to high cost[a] |

[a] Estimated cost for device only: low cost $5–100; moderate cost $100–300; high cost $300–1000

can be mailed to families for them to set up, which eliminates the need for placement by trained technicians, making them suitable for large-scale studies. Moderate correlation with vacuumed dust and airborne dust sampling has been reported for dust mite but also varies by allergen [47].

*Cons*: Settling dust sampling is likely less representative of allergen airway exposure than air sampling devices. Multiple devices are needed for multiple surfaces, and devices must be left out of the way and undisturbed in homes or schools for extended periods of time, typically 7 to up to 28 days.

## Airborne Dust

### Volumetric Air Sampling

Volumetric air sampling employs vacuum pumps at set flow rates (low volume 2–20 L/min, high volume 60 L/min) to pull air through a filter, on which particles are captured [54]. Prior to each use, pumps are calibrated to ensure accurate flow rates, since sample collection, concentration, and size separation depend on flow rate. Filters connected to the pumps are typically housed in a selective size inlet so that the particle sizes that are captured represent respiratory tract penetration. $PM_{10}$, which is particles 10 μm and less in diameter, penetrate the respiratory tract below the level of the larynx and $PM_{2.5,}$ which consists of particles 2.5 μm and less in diameter, penetrate alveoli [56, 57]. Pumps can be active 24 h per day or timed to turn on for a set period, such as 8 h, per day. Volumetric air sampling can be used to collect area or personal samples. Area samplers are placed in homes, schools, or workplaces, and personal samplers are devices worn by an individual. Area samplers should be placed off the ground, away from direct air drafts such as doors and windows. Personal samplers have small pumps that can clip on the belt or can be placed inside a backpack and are connected to a filter holder that is clipped close to the breathing zone. Filters are then placed in eluate for protein extraction and allergens are measured by immunoassay. The total volume of air sampled is calculated from the average flow rate and sampling time during the sampling period. Allergen concentrations are expressed in mass of allergen per volume of air sampled ($ng/m^3$ or $\mu g/m^3$).

*Pros:* Volumetric air sampling is a better representation of allergen that enters the airways than reservoir sampling. It allows for easy comparability between studies since methods are standardized and the quantity of allergen is expressed as a concentration of allergen per volume of air sampled. Size-selective inlets can allow for estimation of the quantity of allergen that penetrates the respiratory tract.

*Cons:* Volumetric air sampling requires specific equipment, calibration, and trained staff, which greatly increases the cost compared to reservoir or settled dust sampling devices. Pumps need to be plugged into electricity or have a battery (typically limited to < 12 h of sampling) and can be noisy.

### Furnace Filters

Recently, home furnace filters have been postulated as a means to sample home air without the need for volumetric sampling pumps. In one study from 2015, disposable, standard 1-in high-efficiency furnace filters were placed in home furnaces for an average of 135 days [58••]. Filters were then collected and vacuumed with a HEPA-rated vacuum to remove collected dust [58••]. Dust was sieved, protein was extracted, and allergen was measured using immunoassay. Another method would be to extract the particles from the filter, as many particles will remain embedded in the filter despite vacuuming; however, in a study focused on sampling DNA using furnace filters, vacuuming filters was superior to cutting or swabbing filters, although is it unknown if this applies to allergens [59]. When compared to floor dust from the family's home vacuum, good correlation was seen for small particle allergens (cat, dog, mouse), but poor correlation was seen for large particle allergens (dust mite, cockroach) [60••]. Allergen can be reported in mass concentration, i.e., mass of allergen per gram of dust recovered.

*Pros*: Using existing furnace filters does not need extra equipment, making this approach inexpensive and easily feasible. Furnace filters may offer a better representation of air being breathed in by the family than reservoir dust, but further studies are needed to validate this method.

*Cons:* In comparison to volumetric air sampling, there is no specific selective particle size filtering. The homes need to have central heating and cooling, which could limit the applicability in certain geographic regions and exclude low-income populations. There is poor correlation with settled dust for dust mite and cockroach allergens [60••]. Estimates can be made for the flow rates using system characteristics; however, there are no standard units for this measurement. [59]. It is unknown how efficiently vacuuming removes allergen from the filter. Another limitation is that existing furnace filters will vary in their particle collection efficiency across homes, so that samples from different homes may not be comparable. The samples are also only reflective of airborne allergen during periods of time when either the heating or cooling system is in use.

### Ionic Sampling: ICDs

Ion-charging devices (ICDs) capture particles by creating a positive field through which particles pass, and the now positively charged particles adhere to negatively charged plates or electrode strips [61]. The plates that capture the particles can be wiped with filters from which protein is extracted, or electrodes can be placed directly in the eluate and centrifuged. The

volume of air sampled can be calculated as the sampling time is measured and flow rate can be estimated with these devices. ICDs can be mailed directly to patients and are plugged into an outlet in the home. Allergen collected is quantified by immunoassay and reported as mass of allergen per $m^3$ of air.

*Pros*: ICDs are nearly silent and are compact. They are easy to use and can be mailed directly to families. They sample from the air at relatively high flow rates (~ 90 L/min) and since flow rate is estimated and time is known, concentrations can be expressed in standardized units for comparability with other methods.

*Cons*: While one study suggested a moderate correlation between ICDs and volumetric air sampling for cat, dog, and mouse allergens, absolute concentrations collected by ICDs were orders of magnitude lower than those estimated from volumetric air sampling [62••]. In addition, the collection efficiency is low for smaller particles, so this device may better reflect exposure to large allergens such as dust mite and cockroach [63••].

## Personal Sampling Devices

Personal sampling devices include intra-nasal samplers and personal volumetric air samplers and are designed to be worn in the breathing zone, including in the nose, or on the collar or can be placed on the pillow during sleep.

### Intra-Nasal Samplers

Intra-nasal air samplers (NASs) are worn inside the nose and utilize an adhesive strip to collect most particles 10 μm in size and approximately 50% of particles 5 μm in size [64•]. NASs are typically worn for 15–30 min intervals (up to 4 h) and offer insight into the allergen composition of airborne particles in particular settings; however, if the wearer breathes through their mouth instead of their nose during the sampling period, particles will bypass the nasal sampler, so estimates of exposure will be an underestimate of true exposure. Immunostaining is used to quantify allergen concentrations, which are reported in NAS counts, where 1 count equals 1 observed allergen-bearing particle.

### Personal Volumetric Air Samplers

Personal volumetric sampling devices are worn in the breathing zone to collect a sample that approximates breathable air. Inlets are attached to collars or shirts and incorporate portable battery-operated pumps running at ~ 2 L/min which clip to the waist/belt or shoulder straps. These devices collect samples which reflect an average concentration of allergen exposure during the time worn. Additionally, time-resolved personal volumetric sampling devices rotate on a timer and allow for reporting over smaller units of time. Time-resolved personal volumetric sampling devices use a small adhesive plate which rotates beneath an inlet slot collecting particles for a set period of time. For example, the device could be set to rotate every hour for 8 h, allowing for even more finely tuned temporal trends to be reported [65••]. Allergen proteins are extracted and immunoassay is used to quantify allergen in units of μg/$m^3$ air.

*Pros*: Personal sampling devices better estimate daily and, for time-resolved devices, temporal exposures, and can be used in multiple settings. NAS can provide a good approximation of breathable allergens, if the wearer breathes through the nose only. Personal volumetric air sampling devices are well suited for the study of occupational allergen exposure, such as in lab animal workers, as they can capture exposure over a workday.

*Cons:* Personal sampling devices can be expensive, noisy, and cumbersome, thus are usually worn for short periods of time. NAS only captures air breathed through the nose and is only worn for short periods of time, so that they miss exposure through the mouth and only reflect very short-term exposures.

## Conclusions

Several methods exist for sampling indoor allergen exposure in dust and air samples. In general, reservoir dust sampling is less expensive and is possible for families to perform [51, 52•, 53•]. Airborne dust sampling can be more expensive, with volumetric air sampling requiring trained technicians, and may better quantify cat, dog, and mouse allergen exposure, as they are more readily airborne for longer periods of time [47•, 49, 54]. Airborne dust samples offer a better representation of breathable air; however, which sampling method one chooses to deploy should take into account the research question. Whether dust or air sampling is better for studies of health associations is not clear. Personal sampling devices can capture an individual's exposure throughout the day and can provide temporal trends when using a time-resolved device. When choosing an appropriate sampling device, it is important to consider clinical and public health implications, occupational health effects, and the research question in addition to cost, ease of use, particle size of the allergen of interest, and approximation of airway exposure.

## Compliance with Ethical Standards

**Conflict of Interest** Dr. Matsui reports grants from Inspirotec outside the submitted work. Dr. Wood reports grants from NIAID, DBV, Astellas, Aimmune, Sanofi, Regeneron, and personal fees from Up to Date and AAAAI, outside the submitted work. The other authors declare no conflicts of interest relevant to this manuscript.

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•• Of major importance


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