

Characterizing particle resuspension from mattresses: chamber study

Abstract People spend approximately one-third of their lives sleeping, where they can be exposed to a myriad of particle-bound biological agents and chemical pollutants that originate within mattresses and bedding, including allergens, fungal spores, bacteria, and particle-phase semi-volatile organic compounds. Full-scale particle resuspension experiments were conducted in an environmental chamber, where volunteers performed a prescribed movement routine on an artificially seeded mattress. Human movements in bed, such as rolling from the prone to supine position, were found to resuspend settled particles, leading to elevations in airborne particle concentrations. Resuspension rates were estimated for the size fractions of 1–2 μm , 2–3 μm , 3–5 μm , 5–10 μm , and 10–20 μm , and were in the range of 10^{-3} to 10^1 h^{-1} . Particle size had the most significant impact on the resuspension rate, whereas dust loading, volunteer body mass, and ventilation rate had a much smaller impact. Resuspension increased with the intensity of a movement, as characterized by surface vibrations, and decreased with repeated movement routines. Inhalation exposure was characterized with the intake fraction metric. Intake fractions increased as the particle size and ventilation rate decreased and ranged from 10^2 to 10^4 inhaled particles per million resuspended, demonstrating that a significant fraction of released particles can be inhaled by sleeping occupants.

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Practical Implications

Full-scale chamber experiments with human volunteers demonstrate that body movements in bed can resuspend settled particles from mattresses, leading to elevated airborne particle concentrations in both the breathing zone and bulk air of the chamber. Numerous variables influence resuspension, including particle size and intensity of a specific body movement. The results suggest that human-induced resuspension in the sleep microenvironment may play an important role in contributing to our inhalation exposure to mattress dust pollutants.

Nomenclature

a	Chamber ventilation rate (h^{-1})	$C_{i,\text{Bulk Air}}(t)$	Particle number concentration in the bulk chamber air as measured at the bulk air OPC sampling location (# particles/ m^3)
A_M	Seeded mattress (top surface) surface area (m^2)	$C_{i,\text{Bulk Air, Clean}}(t)$	Particle number concentration in the bulk chamber air as measured at the bulk air OPC sampling location during the clean set (# particles/ m^3)
APS	Aerodynamic particle sizer	$C_{i,\text{BZ}}(t)$	Spatially averaged BZ particle number concentration, average
ATD	Arizona Test Dust		
BZ	Breathing zone		
C_{Average}	Average particle number concentration at a given sampling location		

$C_{i, \text{BZ, Clean}}(t)$	of BZ right, BZ left, and BZ middle OPC sampling locations (# particles/m ³) Spatially averaged BZ particle number concentration, average of BZ right, BZ left, and BZ middle OPC sampling locations, during the clean set (# particles/m ³)
$\overline{C_{i, \text{BZ, Set}}}$ and $\overline{C_{i, \text{BZ, Decay}}}$	Time-averaged and spatially averaged BZ particle number concentration, average of BZ right, BZ left, and BZ middle OPC sampling locations, during the movement set and decay period, respectively (# particles/m ³)
iF_i	Intake fraction (part per million, ppm)
$\overline{iF_i}$ or iF_{Average}	Time-averaged intake fraction (part per million, ppm)
k_i	Deposition rate (h ⁻¹)
$L_{i,0}$	Initial mattress dust loading (# particles/m ²)
$L_i(t)$	Continuous mattress dust loading during movement set (# particles/m ²)
$\overline{L_i}$	Time-averaged dust loading during movement set (h ⁻¹)
OPC	Optical particle counter
Q_B	Volumetric breathing rate (m ³ /h)
RR	Resuspension rate (h ⁻¹)
$RR_i(t)$	Resuspension rate during movement set (h ⁻¹)
$\overline{RR_i}$ or RR_{Average}	Time-averaged resuspension rate during movement set (h ⁻¹)
RR_{Movement}	Time-averaged resuspension rate for each individual movement (h ⁻¹)
Δt	Time-step (sampling interval of particle sampling instrument) (s)
Δt_{Set} or t_{Set} and t_{Decay}	Duration of movement set and decay period, respectively (min)
V_C	Chamber volume (m ³)

Introduction

The sleep microenvironment is an important, yet understudied, indoor space. It can be defined as the space encompassing a mattress, pillows, bedding, and volume of air above these items that include both an individual's breathing zone (BZ) and thermal plume. There are several defining attributes of this microenvironment that make it unique from both an indoor air quality and exposure/health perspective, including

significant exposure period, roughly equating to one-third of our lives; diversity of pollutants and pollutant sources; and potential for elevated exposures due to the source-proximity effect.

Humans spend a considerable amount of time sleeping. According to the U.S. Environmental Protection Agency's (EPA) Exposure Factors Handbook (EFH) data set (EPA Activity ID = 14500, sleep or nap activity), the average sleep duration for the U.S. mean age group of 37 years (U.S. EPA 2009) is 8.2 h/day, with longer sleep periods for infants, children, and the elderly. Applying the U.S. EPA EFH data set to the National Human Activity Pattern Survey (NHAPS) study conducted by Klepeis et al. (2001), adults spend about 34% of their day in the sleep microenvironment, which equates to about 50% of the time they spend in a residence and 39% of the time they spend indoors. The magnitude of the sleep exposure period makes the sleep microenvironment particularly important in contributing to both our acute and chronic exposures to various pollutants originating in mattresses and bedding.

The seemingly innocuous sleep microenvironment can be home to a diversity of chemical pollutants and biological agents, some of which can impact human health. Mattresses are possible sources of a myriad of chemical species, such as volatile organic compounds (VOCs), plasticizers, flame retardants, and unreacted isocyanates (Boor et al., 2014; Stapleton et al., 2011). Furthermore, mattresses, pillows, and bedding serve as an accumulation zone for a diverse spectrum of particles, many of which are of biological origin.

Biological matter in mattress dust consists of a wide range of organisms and their associated allergens. House dust mite allergens (Der p 1, Der f 1, Der p 2, and Blo t 5), along with cat (Fel d 1), dog (Can f 1), and cockroach (Bla g 2) allergens have been detected in mattress dust, with concentrations ranging over several orders of magnitude, from <1 to >10³ µg/g of mattress dust (Instanes et al., 2005; Leung et al., 2011; Mihrshahi et al., 2002; Su et al., 2001; Wu et al., 2009).

A variety of fungal genera and species are commonly found in mattress dust, including *Penicillium* spp., *Cladosporium* spp., *Aspergillus fumigatus* spp., *Alternaria* spp., *Eurotium* spp., *Epicoccum*, among many others (Begum et al., 2012; Hicks et al., 2005; Jovanovic et al., 2004; Vogel et al., 2008; Woodcock et al., 2006). Mattresses are an ideal fungal culture medium, given the high moisture levels (humans produce approximately 100 l of sweat in bed per year) and elevated surface temperatures around a sleeping human (approximately > 30°C) (Woodcock et al., 2006). Concentrations are typically in the range of 10³ to 10⁴ colony-forming units/g of mattress dust.

The sleep microenvironment is also home to an array of bacteria, many of which are associated with human origin (skin, oral, intestinal/fecal, and genital)

and specifically, the shedding of human skin (e.g., Hospodsky et al., 2012; Täubel et al., 2009). Examples of bacteria identified in mattress dust include *Staphylococcus*, *Lactobacillus*, *Streptococcus* sp., *Lactococcus*, *Bacillus* sp., *Listeria* spp., *Zoogloea* sp., *Corynebacterium tuberculostearicum*, *Moraxella* sp., and *Staphylococcus sciuri* sp., among a host of others (Ege et al., 2012; Korthals et al., 2008; Täubel et al., 2009). Bacterial endotoxin (the biologically active lipopolysaccharide (LPS) of gram-negative bacteria) levels are typically in the range of 10^3 to 10^5 endotoxin units/g of mattress dust. Mattress dust may also contain significant quantities of skin cells, as the human body sheds about 5×10^8 skin cells per day (Weschler et al., 2011).

In addition to particles of biological origin, semi-VOCs (SVOCs), originating in the mattress foam or elsewhere in a residence, may also accumulate in mattress dust due to their low volatility and high molecular weight. Phthalate plasticizers have been detected at levels of 10 – 10^2 $\mu\text{g/g}$ of mattress dust (Hsu et al., 2012), and brominated and organophosphate flame retardants have been detected at levels of <1 to 10^3 ng/g mattress dust (Ali et al., 2012).

Despite extensive research to characterize particulate pollutants in mattress dust, there is a paucity of research on how these pollutants are removed from mattress dust deposits and transported within the vicinity of the human body in bed. The physical process of settled particles detaching from a surface and becoming airborne through application of various aerodynamic and mechanical removal forces is referred to as resuspension. Previous field and laboratory experimental research have shown that human activities, such as walking, can induce resuspension of settled dust from indoor surfaces (Ferro et al., 2004a,b; Karlsson et al., 1999; Qian and Ferro, 2008; Qian et al., 2008; Thatcher and Layton, 1995; Tian et al., 2014; You and Wan, 2014). Resuspension can be influenced by numerous factors, such as characteristics of the particle deposit and deposition surface, airflow dynamics, environmental conditions, and intensity of the human activity (see reviews by Boor et al., 2013a and Qian et al., 2014). It is likely that human movements in bed can resuspend mattress dust particles, thereby serving as a source mechanism for the various biological and organic particle-phase pollutants.

Human activities in bed can occur during periods of wakefulness and throughout the extended sleep state. Although the absence of voluntary motor behavior is a characteristic of the sleep state, movements are commonly reported, ranging from about 10 significant body posture shifts (e.g., Aaronson et al., 1982), such as rolling from the supine to prone position, to several hundred smaller body movements (e.g., Azumi et al., 1977). Body movement frequencies can range from <0.1 to 1 body movements per sleep minute, depending

on sleep stage and age, among other factors (Giganti et al., 2008; Shimohira et al., 1998; Wilde-Frenz and Schulz, 1983).

Elevated inhalation exposures to resuspended particle-phase mattress dust pollutants can occur due to the source-proximity effect, in which pollutant concentrations near a source are greater than those in the bulk air of a room. The source-proximity effect may be influenced by a number of factors, such as the spatial proximity of a sleeping person's BZ to the source, incomplete mixing of bedroom air, concentration gradients near an actively emitting source, the personal cloud due to human-induced particle resuspension, and the buoyant human thermal plume (Laverge et al., 2013; Mage and Ott, 1996; McBride et al., 1999; Rim and Novoselac, 2009, 2010; Wallace, 1996). Laverge et al. (2013) simulated the release of gaseous pollutants from an adult mattress with an inert tracer gas and found the BZ concentrations for an adult thermal manikin to be significantly greater than those measured in the bulk air, typically by a factor of 1.1 to > 2 .

The primary aim of this investigation is to fill knowledge gaps in the literature, particularly as related to human-induced particle resuspension from mattresses and bedding. The impact of particle size, mattress dust load, volunteer body mass, ventilation rate, repeated movement sets, and movement intensity on human-induced resuspension from mattresses was quantified.

Materials and methods

Experimental design

Full-scale experiments were conducted in an environmental chamber with 10 human volunteers. A detailed experimental matrix is presented in Table S1 of the Supporting Information (SI) section. Mattress dust loads are typically in the range of 0.1 to > 1.0 g/m^2 , as reported in field measurements by Gehring et al. (2004), Chen et al. (2007), Giovannangelo et al. (2007), Rennie et al. (2008), Tischer et al. (2011), and Wu et al. (2012). To represent this range in mattress dust loading, two dust loads were examined: 0.1 and 1.0 g/m^2 . For all experiments, volunteers were instructed to perform a prescribed movement routine on an artificially seeded twin-size coil mattress. Airborne particle number concentrations were measured in both the bulk chamber air and volunteer's BZ. Twenty-six experiments were conducted (with 10 volunteers), each with two-repeated movement routine sets, for a total of 52 sets. Although in this investigation only a wrapped mattress was studied, a complementary study by Spilak et al. (2014) examined the impact of pillows, blankets, and bedding arrangements on resuspension.

Particle deposit generation

The test mattress was artificially seeded in a 2.8 m³ seeding chamber. The seeding chamber was constructed with styrofoam panels mounted to a wood frame and was internally lined with grounded aluminum foil to reduce deposition to the chamber walls. The mattress was first wrapped in two layers of 225-thread count bed sheets (60% cotton and 40% polyester) to reduce contamination of the mattress, which was re-used for each experiment. Before seeding, the bed sheets were washed in a standard wash cycle with detergent and then air-dried for at least 48 h. The wrapped mattress was positioned at the bottom of the seeding chamber, where it was seeded with a deposit of polydisperse (1–20 μm) ISO 12103-1 A1 Ultrafine Arizona Test Dust (ATD) (Powder Technology Inc., Burnsville, MN, USA) (Figure 1). ATD has been used in full-scale resuspension experiments and was selected for its known size distribution and ease of generation. ATD also offers insight into the resuspension of actual mattress dust particles that are of similar size, including mite and animal allergen particles (<1 to > 20 μm, e.g., O'Meara and Tovey, 2000; Chang and Gershwin, 2004), fungal spores (1–4 μm, Reponen et al., 2001), fungal fragments (<1 μm, Reponen et al., 2007), bacteria (1 to > 7 μm, Górný et al., 1999; Melkin et al., 2002), and skin flakes (40 × 30 × 2 μm).

The ATD was contained within four aerosolizing canisters positioned at the top of the seeding chamber and was aerosolized with pressurized air (described in further detail in Boor et al., 2011, 2013b). Six small mixing fans were used to improve mixing conditions and the uniformity of particle deposition to the mattress. The mattress remained in the seeding chamber for a 24-h conditioning period to ensure deposition of the entire size distribution of the ATD. Relative humidity was recorded with a HOBO data logger (Model U12-012, HOBOware Pro, Onset Computer Co., Bourne, MA, USA) and remained in the range of

52–59% across all experiments. Deposited particles were collected on nine microscope slides (25 × 75 mm) distributed across the mattress surface. The ATD loading on the microscope slides was then measured gravimetrically with an analytical balance (Model AB135-5, Mettler-Toledo International Inc., Columbus, OH, USA). The resulting dust loads for each experiment are presented in Table S1 and were typically within 10–20% of the nominal value.

Chamber configuration and instrumentation

Resuspension experiments were performed in a 14.75 m³ stainless steel chamber. Influent air was filtered with an in-duct HEPA filter and supplied via a displacement ventilation diffuser. The chamber remained positively pressurized. The test mattress was placed above a box spring and steel frame, located approximately at the center of the chamber. A three-axis linear accelerometer (10 Hz sampling frequency, Model LIS302DL, STMicroelectronics, Geneva, Switzerland) was mounted to the wrapped mattress surface, near the volunteer's head region, to monitor surface vibrations. Air velocities above the bedding surface were also recorded in several additional experiments (measured with 5 Hz omnidirectional anemometers, Model HT-400, Sensor Electronics, Gliwice, Poland).

Four particle sampling instruments were positioned throughout the chamber, as shown in Figure 1. One optical particle counter (OPC, 0.05 Hz sampling frequency over which concentration is averaged, AeroTrak Model 8220, TSI Inc., Shoreview, MN, USA) ('bulk air') was positioned at 0.83 m above the mattress surface, at the approximate midpoint between the mattress surface and the chamber exhaust. This position was used to approximate the particle concentration in the bulk chamber air (Figure 1). To measure the BZ particle concentration, two OPCs and one aerodynamic particle sizer (APS, 1 Hz, Model 3321, TSI Inc.) were used, as shown in Figure 1. The APS

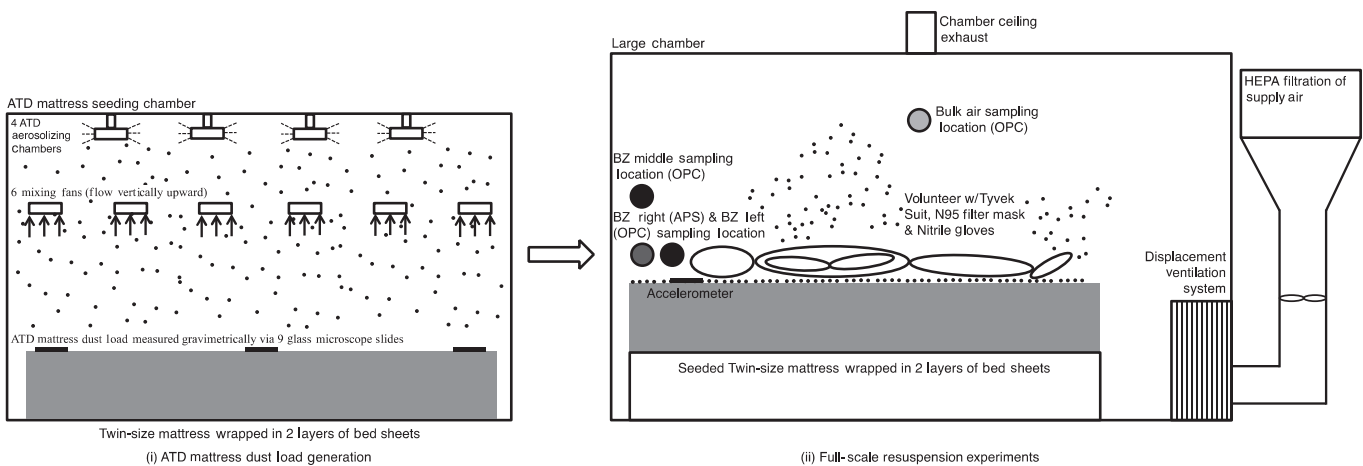


Fig. 1 Mattress seeding process and large chamber setup for full-scale resuspension experiments

(‘BZ right’) and one OPC (‘BZ left’, 0.1 Hz, AeroTrak Model 9306, TSI Inc.) represent the approximate height of the BZ of an occupant lying in the prone position or on their side (2.5 cm above the mattress surface). Another OPC (‘BZ middle,’ 0.1 Hz, AeroTrak Model 9306, TSI Inc.) was positioned 25 cm above the mattress surface to represent the approximate BZ height for an occupant lying in the supine position. To address the variability in the particle size classification by the three OPCs, the instruments were corrected against the APS in co-location measurements using aerosolized ATD and correction factors were applied on a size-resolved basis. The particle concentrations for all sampling instruments were divided into five particle size fractions: 1–2, 2–3, 3–5, 5–10, and 10–20 μm , corresponding to the size distribution (and size fractions) of the ATD.

Volunteer movement routine and experimental sequence

Each volunteer was instructed to perform a routine of five movements on the mattress, designed to represent common movements of varying intensities that an occupant may perform while in bed. Upon entering the chamber, the volunteer performed the following routine (Figure 2): M1, sit on mattress (then hold still in position for 2.5 min); M2, lay in the supine position (then hold still in position for 2.5 min); M3, full 360° rotation to supine position (then hold still in position for 2.5 min); M4, lay in prone position (then hold still in position for 2.5 min); and M5, lay in supine position (then hold still in position for 2.5 min). The entire movement set lasted 12.5 min. All volunteers wore a Tyvek clean suit outfit, with booties and a hood (Model TY122 S, DuPont™), filter mask (OSHA & NIOSH N95 rating, Model 8210, 3M™), and Nitrile gloves. The outfit was selected to protect the volunteer

from particle exposure and to prevent the volunteer from acting as a source of particles.

The movement routine was repeated three times for each resuspension experiment, as outlined in the experimental sequence, Figure 3. First, the volunteer performed the routine on an unseeded mattress, referred to as the ‘clean set,’ to evaluate background particle concentrations. The seeded wrapped mattress was then carefully placed in the chamber. Background particle concentrations were allowed to decay for a period of 30 min. The volunteer then performed two sets of the movement routine, ‘set 1’ and ‘set 2,’ which are separated by a 30-minute decay period. Set 2 offers insight into how resuspension changes in time after numerous movements on the seeded mattress. Set 2 was followed by an hour-long decay period.

Figure 3 illustrates the characteristic particle number concentration profile throughout the entire experimental sequence (Note: particle number concentration is presented on logarithmic scale and is a schematic, not actual data.) Short-term concentrations peaks were observed at the commencement of each movement, M1–M5, during the clean set (suggesting the resuspension of residual particles and zeolite particles [originating in the detergent] on the bedding), set 1 and set 2. Throughout each movement set, a gradual elevation in the particle concentration was observed. The baseline particle concentration continued to increase until the cessation of the movement set, where it was then followed a decay period. The particle concentration profile and experimental sequence can be interpreted as what might occur as an occupant gets into bed (M1), re-positions themselves as they attempt to fall asleep (M2–M5), and then lays still as they enter their sleep cycle (decay periods).

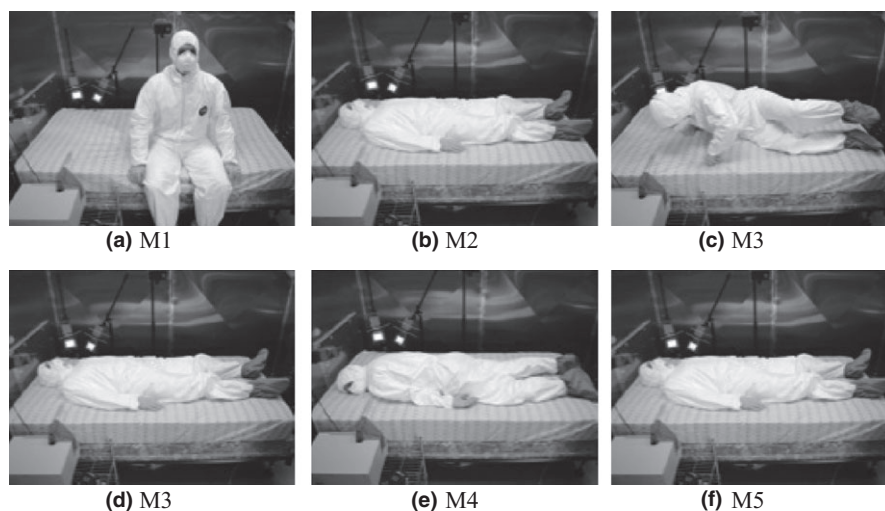


Fig. 2 Volunteer movement routine, (a) movement 1 (M1): sit on mattress, (b) movement 2 (M2): lay in supine position, (c and d) movement 3 (M3): 360° rotation to supine position, (e) movement 4 (M4): lay in prone position, and (f) movement 5 (M5): lay in supine position

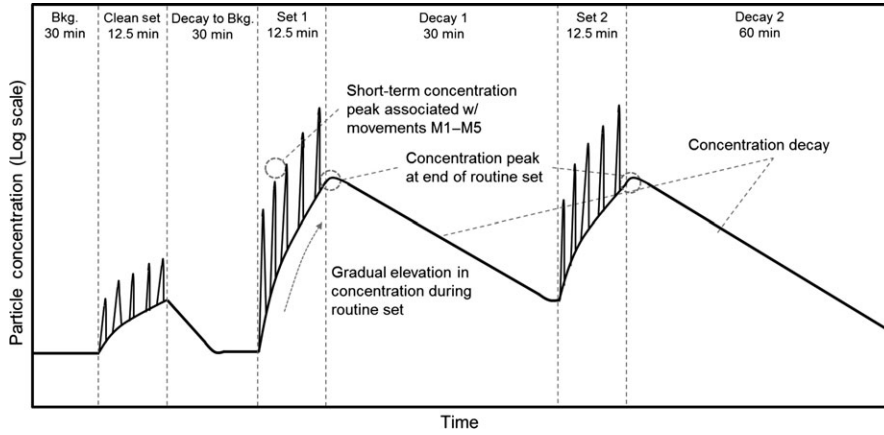


Fig. 3 Characteristic particle number concentration profile during the experimental sequence (Note: figure is for illustrative purposes and does not present actual data)

Resuspension rate estimate

Resuspension can be quantified through the resuspension rate (RR , h^{-1}) metric, defined as the fraction of surface species removed per unit time (Slinn 1978):

$$RR = \frac{\text{resuspension flux}}{\text{surface concentration}}. \quad (1)$$

RR has been widely used by others for indoor particles (Gomes et al., 2007; Oberoi et al., 2010; Qian and Ferro, 2008; Raja et al., 2010; Shaughnessy and Vu, 2012; and Thatcher and Layton, 1995).

For this investigation, RR is determined by applying a two-compartment mass balance (e.g., Qian and Ferro, 2008; Schneider et al., 1999) to model the particle number concentration for each size fraction, i :

$$V_C \frac{dC_{i, \text{Bulk Air}}(t)}{dt} = RR_i(t)L_i(t)A_M - aV_C C_{i, \text{Bulk Air}}(t) - k_i V_C C_{i, \text{Bulk Air}}(t) \quad (2)$$

$$A_M \frac{dL_i(t)}{dt} = k_i V_C C_{i, \text{Bulk Air}}(t) - RR_i(t)L_i(t)A_M. \quad (3)$$

The following expression can then be derived from Equations 2 and 3:

$$A_M \frac{dL_i(t)}{dt} = -V_C \left[\frac{dC_{i, \text{Bulk Air}}(t)}{dt} + aC_{i, \text{Bulk Air}}(t) \right]. \quad (4)$$

The continuous mattress dust loading, $L_i(t)$, can be estimated by integrating Equation 4 from time $t = 0$ to t :

$$L_i(t) = L_{i,0} - \frac{V_C}{A_M} \left[\left(C_{i, \text{Bulk Air}}(t) - C_{i, \text{Bulk Air, Clean}}(t) \right) + a \int_{t_0}^t \left(C_{i, \text{Bulk Air}}(t) - C_{i, \text{Bulk Air, Clean}}(t) \right) dt \right] \quad (5)$$

where $L_{i,0}$ is the initial mattress dust loading. The initial dust loading for each size fraction was estimated using the size distribution provided by the ATD manufacturer. The dust loading at the end of set 1 was used as the initial dust loading for set 2. The bulk air concentration during the clean set is subtracted from the bulk air concentration during sets 1 and 2 at the same time t during the routine. The concentration during the clean set, which remained nearly one to two orders of magnitude lower than that during Sets 1 and 2, includes contributions from non-ATD resuspension (e.g., bedding fibers and zeolite particles in the detergent), infiltration, and filter by-pass. As such, this correction ensures the bulk air concentration represents resuspended ATD particles as best possible. The integral in Equation 5 was estimated using Simpson's rule.

Knowing $L_i(t)$ and $C_{i, \text{Bulk Air}}(t)$, $RR_i(t)$ can be determined using a numerical forward difference approximation with a time-step of $\Delta t = 20$ s (sampling interval of bulk air OPC):

$$RR_i(t + \Delta t) = \frac{V_C}{A_M L_i(t)} \left[\frac{C_{i, \text{Bulk Air}}(t + \Delta t) - C_{i, \text{Bulk Air}}(t)}{\Delta t} + (a + k_i) \left(C_{i, \text{Bulk Air}}(t) - C_{i, \text{Bulk Air, Clean}}(t) \right) \right]. \quad (6)$$

As with the $L_i(t)$, the bulk air concentration during the clean set is subtracted from the bulk air

concentration during sets 1 and 2. The time-averaged dust loading and resuspension rate were then determined for the entire 12.5 min routine ($\Delta t_{\text{Set}} = 12.5 \text{ min.}$) for sets 1 and 2, along with the time-averaged resuspension rate for the duration of each individual movement, M1–M5.

In the above analysis, ATD resuspension is assumed to be the only particle source (after correcting for the clean set concentration). It is assumed that there is negligible track-in of ambient particles. The chamber ventilation rate, a , was measured via CO_2 decay, and

inhaled was determined by integrating the product of the occupant's breathing rate with the concentration of resuspended particles in their BZ (spatial average) during the 12.5-min movement set (corrected for the clean set concentration) and the following decay period (the full 30 min for the first decay period and the first 30 min of the second decay period, for consistency). The total number of particles released was determined by integrating the product of the resuspension rate, continuous dust loading, and seeded surface area. The size-resolved iF can be presented as:

$$iF_i(t) = \frac{\int_{t_0=0}^{t_{\text{Set}}=12.5\text{min}} Q_B(t) (C_{i, \text{BZ}}(t) - C_{i, \text{BZ, Clean}}(t)) dt + \int_{t_{\text{Set}}=12.5\text{min}}^{t_{\text{Set}}+t_{\text{Decay}}=42.5\text{min}} Q_B(t) C_{i, \text{BZ}}(t) dt}{A_M \int_{t_0=0}^{t_{\text{Set}}=12.5\text{min}} RR_i(t) L_i(t) dt} \quad (7)$$

values are listed in Table S1 for each experiment. The deposition rate was determined by calculating the loss rate ($a + k_i$) from the final 1-hour decay period. The average deposition rates for each size fraction were: 1–2 μm : 4.4×10^{-5} , 2–3 μm : 1.6×10^{-4} , 3–5 μm : 3.3×10^{-4} , 5–10 μm : 7.3×10^{-4} , and 10–20 μm : $1.2 \times 10^{-3} \text{ s}^{-1}$. These values are consistent with those reported in the literature (Byrne et al., 1995; Lai et al., 2002; Thatcher et al., 2002). It is assumed that the deposition rates remain the same for the decay period, with no volunteer present, and for the movement sets, with a volunteer present.

Exposure estimate

In the sleep microenvironment, an individual is positioned in very close proximity to the source (settled dust on mattress) with their BZ only centimeters above the mattress surface. Figure S1 shows the average particle concentrations at each of the sampling locations, bulk air, BZ right, BZ left, and BZ middle, along with the spatial BZ average (mean of three BZ sampling locations). The BZ concentrations offer a starting point to estimate an occupant's exposure to resuspended particles.

Occupant exposure was characterized with the intake fraction, iF , metric. The iF for a pollutant is defined as the total mass inhaled per unit mass released from a source and can be expressed on a part per million (ppm) basis (Bennett et al., 2002; Marshall and Nazaroff, 2007). Here, iF is defined as the ratio of the number of particles inhaled to the number of particles which resuspend.

For our particular experimental sequence, the exposure period to resuspended particles is greater than the emission period. Thus, the total number of particles

where $Q_B(t)$ is the occupant's volumetric breathing rate (m^3/h). We assume a temporally constant breathing rate, Q_B , based on data provided by the U.S. EPA EFH (mean of 0.299 m^3/h for adults 21 to > 81 years of age for sleep or nap activity, U.S. EPA, 2009). We then apply a simplified expression to compute the average iF for the entire experimental sequence using time-averaged quantities. As defined below, this is the ratio of the average number of particles inhaled during both the movement set and decay periods to the average number of particles that resuspend during the movement set:

$$\overline{iF}_i = \frac{Q_B (\overline{C_{i, \text{BZ, Set}}} + \overline{C_{i, \text{BZ, Decay}}})}{A_M \overline{RR}_i \times \overline{L}_i} \quad (8)$$

Statistical analysis

Statistical analysis was performed to evaluate the impact of various parameters (excluding the chamber ventilation rate due to a small sample size) on the resuspension rate and intake fraction using Wilcoxon nonparametric, two-related samples tests with statistical software (SPSS[®] version 20.0.0 2011, IBM[®]). P -values equal to or below 0.05 were considered statistically significant.

Results and Discussion

The following sections present the results from this investigation, including particle number concentrations, impact of various parameters on the resuspension rate and intake fraction, a discussion of

resuspension mechanisms, and an overview of exposure to resuspended particles.

Particle number concentration profile

Volunteer body movements on a seeded twin-size mattress were found to resuspend deposited mattress dust (ATD) particles in the range of 1–20 μm . Significant elevations in airborne concentrations of resuspended particles were observed for each individual movement, M1–M5, as shown in a typical concentration profile in Figure 4 for volunteer RSV04. These short-term concentration peaks were approximately one to two orders of magnitude greater than the background concentration, for both movement sets and dust loads. The BZ and bulk air concentrations gradually increased over the entire 12.5-min movement routine. At the cessation of the movement routine, particles concentrations were approximately an order of magnitude greater than background levels. The elevations in airborne particle concentrations follow a similar trend of what has been observed in full-scale walking resuspension studies by others (Ferro et al., 2004a,b; Karlsson et al., 1999; Qian and Ferro, 2008; Shaughnessy and Vu, 2012).

Dust loading had a significant impact on particle number concentration. Concentrations during the movement routine on the mattress seeded with 1 g/m^2 of ATD were typically an order of magnitude greater than those with 0.1 g/m^2 . In general, airborne concentrations reached approximately 10^6 particles/ m^3 for 0.1 g/m^2 and 10^7 particles/ m^3 for 1.0 g/m^2 at the cessation of a movement routine (Figure 4). In general, particle concentrations during the second movement set were only slightly lower than those during the first set. Particle concentrations decayed linearly (on a

logarithmic scale) during both decay stages due to removal via deposition and ventilation. The decay stages represent what an occupant might be exposed to after a resuspension event and during periods of inactivity while sleeping.

Resuspension rate: particle size, movement set, and dust load

Figure 5 includes a summary of the average resuspension rates (time-averaged over 12.5-min movement routine) among the 10 volunteers. The *RRs* were found to range over four orders of magnitude from 10^{-3} to 10^1 h^{-1} . *RR* increases with increasing particle size, by approximately 3 orders of magnitude from 1–2 μm to 10–20 μm . Differences in *RRs* between size fractions were found to be statistically significant (Table S2). The size-dependence of *RR* is expected, given the basic mechanisms of particle detachment from surfaces and the findings of previous particle resuspension studies. For particles in the 1–20 μm size range, resuspension tends to increase with increasing particle size as the ratio of removal forces to adhesion forces increases (Hinds, 1999). The impact of particle size is particularly relevant to the sleep microenvironment, given that particle-phase mattress dust pollutants are associated with different size particles.

RRs tend to decrease from movement set 1 to set 2, and the differences were found to be statistically significant for most particle sizes and both dust loads (Table S4). As discussed in Qian and Ferro (2008), the decay in *RR* may be due to a reduction in the number of particles available for resuspension during periods of human activity, likely due to the distribution of adhesion forces for any given particle size. The slight reduction in *RR* may also be explained by the migration of

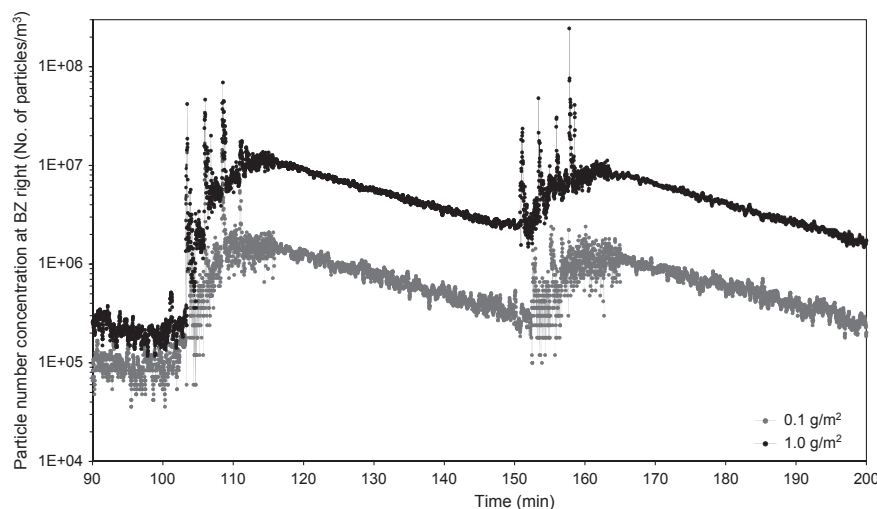


Fig. 4 Example of particle number concentration profile during a resuspension experiment: 1–2 μm , both 0.1 and 1.0 g/m^2 dust loads, sampled at BZ right with APS for volunteer RSV04. Note: figure shows 1 s sampling average during sets 1 and 2, and 10 s sampling average during background and decay periods

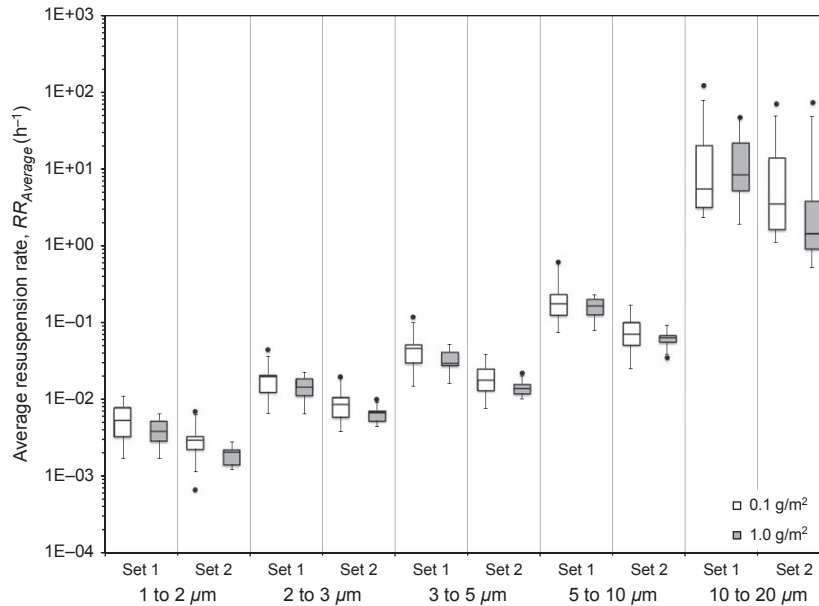


Fig. 5 Average resuspension rates (RR) among 10 volunteers over entire movement routine (M1–M5), for both 0.1 g/m^2 and 1.0 g/m^2 dust loads. Box plots represent interquartile range, whiskers represent the 5th and 95th percentiles, and dots represent outliers

particles deeper into the bed sheet fiber matrix due to pressure applied by the volunteer positioned above, as well as variability in movement technique and style between both movement sets for each volunteer. It is expected that prolonged periods of activity in bed may further reduce the RR throughout a sleep period.

Dust loading appears to have a negligible impact on RR , despite the significant differences observed in particle concentrations. As shown in Table S3, differences in RR between 0.1 and 1.0 g/m^2 were not found to be statistically significant for all particle sizes. Dust loading is an important parameter affecting resuspension, although the impact is much more pronounced when comparing monolayer and multilayer particle deposits (Boor et al., 2013a). For dust loads of 0.1 and 1.0 g/m^2 , particles are very likely deposited as a monolayer along the fiber, with minimal particle-to-particle contact. Thus, the impact of the type of particle deposit is much less pronounced, although resuspension can be influenced by seeding density (no. of particles per deposition area) (Ibrahim et al., 2004). Mattress dust loads are typically in the 0.1 – 1.0 g/m^2 range, although lighter and heavier dust loads are likely, depending on how often bed sheets and the mattress are cleaned and the general cleanliness in a bedroom. The RR s reported in this investigation may not necessarily represent those for sparser or heavier deposits.

The size-resolved RR s estimated for human movement in bed are similar in magnitude to those reported by walking-induced resuspension studies by Qian and Ferro (2008) and Shaughnessy and Vu (2012). It is difficult to make direct comparisons in RR s between studies due to differences in experimental methods,

ventilation systems, particle sampling techniques, RR model assumptions, and movement frequency. It can be concluded, however, that the similar ranges in RR s suggest that particle resuspension associated with human body movements in bed is an important source of mattress dust particles, comparable to particles released from flooring via footfalls.

Resuspension rate: volunteer body mass and BMI, ventilation rate, and movement type

The impact of additional factors on the RR was also investigated (a detailed discussion can be found in the SI section, along with associated figures). Volunteer body mass and body mass index (BMI) had a minimal impact on the RR . Intuitively, resuspension would be expected to increase with body mass; however, it is possible that beyond a certain threshold weight, the removal forces induced by body movements in bed are much more dependent on movement intensity and technique, rather than their body mass alone. The chamber ventilation rate was also found to have a minimal impact on the RR . As the particle loss rate ($a + k$) increases with the ventilation rate, improving ventilation may reduce the period over which an occupant is exposed to resuspended particles after cessation of body movements. Finally, body movements of greater intensity (e.g., M3, 360° rotation of the torso) increased particle resuspension compared with less intense movements (e.g., M1, sitting on the mattress), as shown in Figure 6 for 3 – $5 \mu\text{m}$ particles. A summary of movement-specific RR s can be found in the SI section.

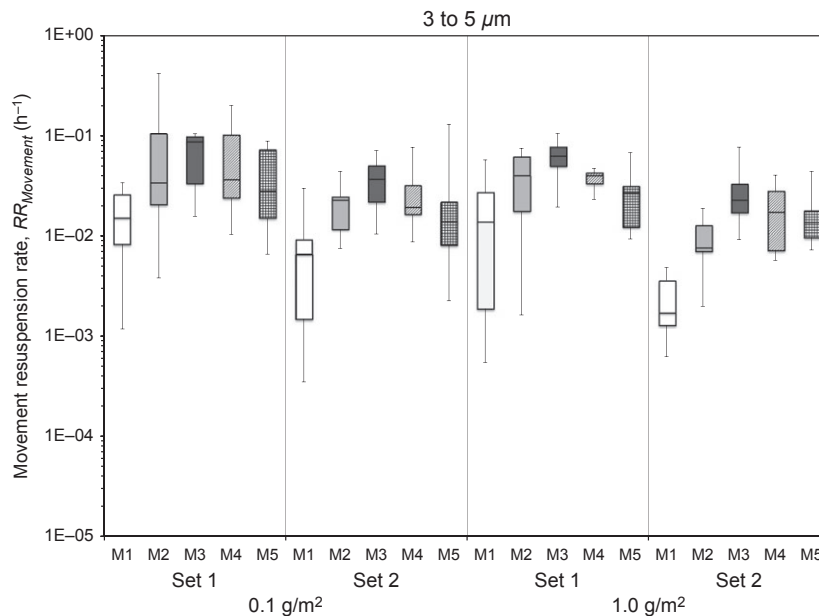


Fig. 6 Average resuspension rates (RR) among 10 volunteers for each individual movement (M1, M2, M3, M4, M5), 3–5 μm (remaining size fractions can be found in Figure S4). Box plots represent interquartile range, whiskers represent the 5th and 95th percentiles, and shading represents specific movements (M1–M5), as denoted on the x -axis

Discussion on resuspension mechanisms: mattress surface vibrations, air bursts, and other factors

Each of the five movements, M1–M5, was associated with a peak in mattress surface vibration, as shown in Figure S5 (a) and (b). Peak surface vibrations were generally between 0.1 and 1 g (9.81 m/s^2) in magnitude. To put these values in perspective, Gomes et al. (2007) reported walking-induced peak floor vibrations of generally $\leq 0.1 g$.

The RR for a specific movement was found to increase with increasing magnitude of surface vibrations. As previously discussed, RR was found to be the greatest for M3: full 360° rotation (Figure 6). The surface vibrations induced by M3 were also the largest of the five movements. Movements of greater intensity, such as a full body rotation, can generate greater surface vibrations, and in turn, increase the magnitude of the associated removal forces, such as the wall vibration force (Theerachaisupakij et al., 2002) and lift-off drag force (Gomes et al., 2007), thereby enhancing particle resuspension. Additionally, M1 was generally associated with the lowest surface vibration magnitudes, and in turn, the lowest RR s.

In addition to surface vibrations, each of the five movements, M1–M5, was associated with a peak in air velocity approximately 1 cm above the mattress surface as measured in a trial set of experiments (Figure S5c). The airflow regime induced by human movements in bed is complex. During movements, pockets of air beneath the loosely bound bed sheet (visible ripples) were observed. Thus, there is likely a combination

of airflow through the porous bedding fabric matrix ('air burst'), as well across the bedding surface. This complex airflow pattern may aid in increasing the aerodynamic removal forces acting on the deposited particles.

The air velocities increased suddenly, suggesting impulsive and highly accelerated airflow, similar to airflows generated by footfalls or descending objects (e.g., Choi and Edwards, 2012; Khalifa and Elhadidi, 2007; Kubota et al., 2009). The impulsive nature of the flow may be considerably more important in inducing resuspension from the bed sheets than the maximum velocities achieved. Ibrahim et al. (2003) found RR s to be two orders of magnitude greater during periods of acceleration compared with steady-state velocity conditions in their wind tunnel study. This is in part due to the additional aerodynamic removal force, known as the Basset force, which can arise as the flow is accelerated (Tadmor and Zur, 1981). The turbulent airflow may also induce vibrations of the bedding fibers. Additionally, Fletcher et al. (2008) found turbulent and impulsive pulsed air jets to resuspend significant fractions of 1–45 μm particles from muslin cloth. Impulsive 'air bursts' may be an important mechanism in detaching settled mattress dust particles.

Mechanical abrasion caused by direct contact between the volunteer and the deposited particles, as well as sections of the bed sheets rubbing against each other, may generate additional removal forces. During the movement routine, it is likely that some fractions of the deposited ATD particles were transferred to the volunteer's clean suit outfit. This contact transfer could

have dual effect of reducing the number of particles available for resuspension from the bed sheet ($L_{i,0}$) and causing secondary resuspension of the transferred particles from the Tyvek clean suit. In regards to the latter, studies have demonstrated that particles can be efficiently resuspended from clothing worn by occupants (Bloor and Dinsdale, 1962; Bohne and Cohen, 1985; Cohen and Positano, 1986; McDonagh and Byrne, 2014; You et al., 2013). Resuspension from the clean suit likely occurred to some extent during the experiments, although it is not considered in the RR and iF analysis.

Intake fraction

Time-averaged intake fractions (iF) were generally in the range of 10^2 – 10^4 inhaled particles per million resuspended, as shown in Figure 7(a).

For particles in the range of 1–10 μm , iF s are generally on the order of 10^3 – 10^4 ppm, and for particles in the range of 10–20 μm , iF s are generally on the order of 10^2 ppm. Although the RR increases with increasing particle size, the opposite is observed for iF . Differences in iF among the different size fractions were found to be statistically significant (Table S2). Thus,

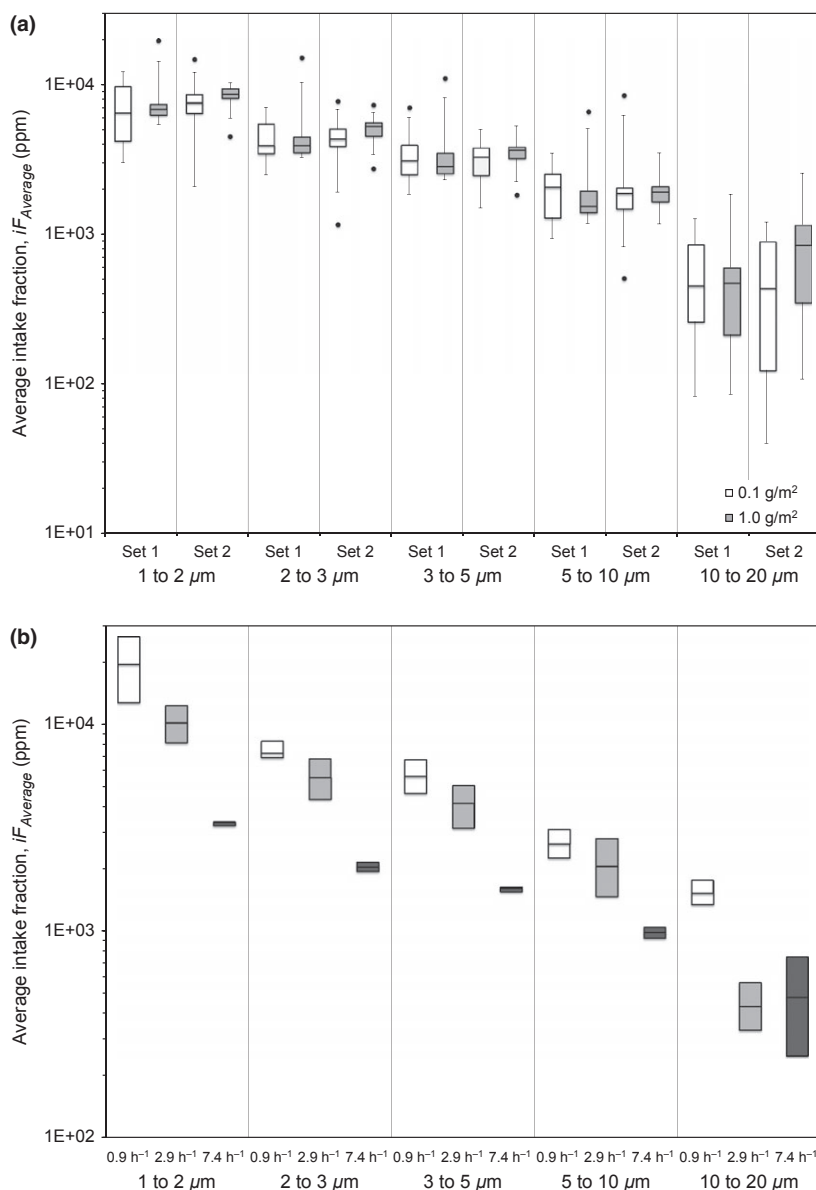


Fig. 7 (a) Average intake fraction (iF) among 10 volunteers over entire movement sequence (M1–M5 and decay), for both 0.1 g/m² and 1.0 g/m² dust loads. Box plots represent interquartile range, whiskers represent the 5th and 95th percentiles, and dots represent outliers. (b) impact of chamber ventilation rate on average intake fraction (iF) over entire movement sequence (M1–M5 and decay) for two volunteers (RSV01 and RSV02). Box plots represent interquartile range and shading represents ventilation rate, as denoted on the x-axis

even though larger particles are more easily resuspended, a greater fraction of smaller particles that resuspend will be inhaled. This is due to a combination of lower deposition rates for smaller particles and greater BZ concentrations for smaller particles, the latter of which is due in part to the size distribution of the ATD used to generate the artificial mattress dust deposits (mass median diameter of $4.5 \mu\text{m}$). The smaller particles have a greater likelihood of being inhaled, rather than be removed via gravitational settling to the mattress surface, compared with the larger particles (Marshall and Nazaroff, 2007; Nazaroff, 2008).

iF was found to be slightly greater for a dust load of 1.0 g/m^2 compared with 0.1 g/m^2 , although a statistically significant difference was not observed. iF remained nearly the same from movement set 1 to set 2. RR was not strongly influenced by the chamber ventilation rate; however, iF increased with decreasing ventilation rate from 7.4 to 0.9 h^{-1} for particles in the $1\text{--}10 \mu\text{m}$ range, as shown in Figure 7(b). Increasing the ventilation rate increases the fraction of particles that are removed from the chamber air rather than inhaled, thus decreasing iF . Low ventilation rates have been reported for naturally ventilated children's bedrooms by Bekö et al. (2010), with a mean ventilation rate of 0.46 h^{-1} , and rates as low as 0.1 h^{-1} . Lower ventilation rates may lead to elevated exposures and increase the iF beyond values reported here, while proper ventilation strategies and effective use of in-duct and portable particle filtration technologies may reduce exposure and iF below values reported here.

iFs on the order of 10^2 and 10^4 ppm are similar in magnitude to those reported for indoor particle sources (e.g., Lai et al., 2000; Marshall and Nazaroff, 2007). Lai et al. (2000) reported iFs in the range of $10^3\text{--}10^5$ ppm for nonreactive pollutants in a single zone residence with one to five occupants based on a modeling analysis. Size-resolved iFs for a single, well-mixed building were found to be approximately 7.5×10^3 for $1 \mu\text{m}$ particles at a ventilation rate of 0.2 h^{-1} , 10^3 for $1 \mu\text{m}$ particles at a ventilation rate of 2.0 h^{-1} , and 10^2 for $10 \mu\text{m}$ particles at both ventilation rates. The impact of particle size and ventilation rate is similar to the trend observed in this investigation for resuspended mattress dust particles.

Implications for inhalation exposure

The non-negligible fractions of resuspended particles that are inhaled are in part due to the important role of the source-proximity effect on exposure to pollutants originating in the sleep microenvironment. The ratios of the spatial BZ average concentrations to the bulk air concentrations were (mean \pm s.d. among all tests): $1\text{--}2 \mu\text{m}$: 1.94 ± 0.52 , $2\text{--}3 \mu\text{m}$: 1.26 ± 0.30 , $3\text{--}5 \mu\text{m}$: 1.07 ± 0.23 , $5\text{--}10 \mu\text{m}$: 1.63 ± 0.38 , and $10\text{--}20 \mu\text{m}$:

1.10 ± 0.34 . Similar findings have been reported for the distribution of SF_6 tracer gas released from a test mattress by Laverge et al. (2013) and for VOCs emitted from a crib mattress by Boor et al. (2014). Additionally, for a person to be exposed to particles $\geq 10 \mu\text{m}$, which have high settling velocities (on the order of approximately 10^{-3} m/s), close proximity of the BZ to the particle deposit is important, as is the case in the sleep microenvironment.

Study limitations

The RR and iF values reported in this investigation should be viewed as best estimates that are specific to the experimental setup and the set of prescribed movements that the volunteers undertook. There is uncertainty in extrapolating these results to actual bedroom environments, where there are numerous complexities that cannot be captured in a laboratory setting. There is also a wide variability in the type of ventilation systems installed in a residence, mixing conditions in a room, characteristics of actual mattress dust particles on an occupant's bed (surface features, size distribution, composition, shape, etc.), moisture levels near bedding surfaces, bedding arrangements and materials, and occupant movement patterns in bed, all of which are parameters that may impact resuspension and exposure.

The resuspension rate analysis is based upon a two-compartment model (bulk chamber air and surface loading). A two-compartment model was selected over a three-compartment model (BZ, bulk chamber air, and surface loading) due to the complexity of defining the inner-zonal air exchange between the BZ and bulk chamber air compartments and lack of experimental data on the inner-zonal air exchange rate (see Earnest and Corsi, 2013). A three-compartment model would improve the accuracy of the RR estimate; however, the two-compartment model provides a reasonable estimate of RR . Additionally, the particle concentration in the bulk chamber air was assumed to be uniform and well represented by the OPC positioned at the fixed bulk air monitoring location. Resuspension mixing tests were completed with five OPCs positioned throughout the bulk chamber air to evaluate this assumption. The percent difference in resuspended particle concentrations measured at each location with the reference location, bulk air, was found to be below 30% for all size fractions, and below 20% for the total particle concentration, sum of $1\text{--}20 \mu\text{m}$, similar to the mixing conditions reported in Qian and Ferro (2008).

Conclusions

Full-scale chamber experiments were conducted to investigate human-induced particle resuspension from mattresses. Significant elevations in airborne particle

concentrations were observed as human volunteers performed prescribed routines of five movements on an artificially seeded mattress wrapped in two layers of bed sheets. Resuspension rates were estimated for ATD particles in the 1–20 μm size range. Resuspension rates increased with increasing particle size, decreased with repeated movement sets, and were in the range of 10^{-3} to 10^1 h^{-1} . Resuspension generally did not show a strong association with (for the ranges examined) dust loading, volunteer body mass and body mass index, and chamber ventilation rate. Movements of greater intensity, such as a full rotation of the body, were found to be associated with higher resuspension rates than lower intensity movements, such as sitting on the mattress. The possible mechanisms of resuspension likely include a combination of surface vibrations of the bedding fibers, aerodynamic removal forces associated with impulsive ‘air bursts’ through the porous bedding, mechanical abrasion, and contact transfer.

Intake fractions, as estimated from breathing zone particle number concentrations, were in the range of 10^2 – 10^4 inhaled particles per million resuspended, demonstrating that a significant fraction of resuspended particles may be inhaled by a sleeping occupant. Additionally, elevated concentrations after the completion of a movement routine suggest that people may be exposed to resuspended particles as they lay still in bed following a resuspension event. The results suggest that resuspension is an important source mechanism for particle-phase pollutants originating in mattress dust.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Fig. S1. Spatial distribution of average particle concentration over entire movement routine (M1–M5, Set 1)

among all sampling locations: bulk air, BZ right, BZ left, BZ middle, and spatial BZ average for each experiment, highlighting the source-proximity effect.

Fig. S2. Average resuspension rates (RR) over entire movement routine (M1–M5) as a function of volunteer body weight, (a) 0.1 g/m^2 and (b) 1.0 g/m^2 dust loads.

Fig. S3. Average resuspension rates (RR) over entire movement routine (M1–M5) as a function of volunteer body mass index (BMI), (a) 0.1 g/m^2 and (b) 1.0 g/m^2 dust loads.

Fig. S4. Average resuspension rates (RR) among 10 volunteers for each individual movement (M1, M2, M3, M4, M5), (a) 1–2 μm , (b) 2–3 μm , (c) 3–5 μm , (d) 5–10 μm , and (e) 10–20 μm . Box plots represent interquartile range, whiskers represent the 5th and 95th percentiles, and shading represents specific movements (M1–M5), as denoted on the x -axis.

Fig. S5. (a) Example profile of mattress surface vibrations during a resuspension experiment, (b) the distribution of peak mattress surface vibrations (direction normal to surface, magnitude) across all resuspension experiments for each movement, (c) example of air velocity 2.5 cm above mattress surface, and (d) possible mechanisms that may be responsible for particle resuspension from the mattress and bedding fabric surfaces. Box plots represent interquartile range and whiskers represent the 5th and 95th percentiles.

Fig. S6. (a) impact of ventilation rate on particle concentration during movement routine and decay periods, (b) impact of ventilation rate on average resuspension rate (RR) over entire movement routine (M1–M5) for two volunteers (RSV01 & RSV02). Box plots represent interquartile range and shading represents ventilation rate, as denoted on the x -axis.

Table S1. Experimental matrix.

Table S2. Impact of particle size on average resuspension rate (RR) and intake fraction (iF), P -values from Wilcoxon non-parametric, two-related samples tests.

Table S3. Impact of dust load on average resuspension rate (RR) and intake fraction (iF), P -values from Wilcoxon non-parametric, two-related samples tests.

Table S4. Impact of movement set on average resuspension rate (RR) and intake fraction (iF), P -values from Wilcoxon non-parametric, two-related samples tests.

Table S5. Impact of volunteer body mass on average resuspension rate (RR), P -values from Wilcoxon non-parametric, two-related samples tests.

Table S6. Impact of volunteer body mass index on average resuspension rate (RR), P -values from Wilcoxon non-parametric, two-related samples tests.

Table S7. Impact of each individual movement (M1–M5) on average resuspension rate (RR), P -values from Wilcoxon non-parametric, two-related samples tests.

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