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# Impact of bedding arrangements, pillows, and blankets on particle resuspension in the sleep microenvironment

Michal P. Spilak [a, *], Brandon E. Boor [b], Atila Novoselac [b], Richard L. Corsi [b]

[a] Aalborg University, Danish Building Research Institute, Department of Construction and Health, Copenhagen, Denmark
[b] The University of Texas at Austin, Department of Civil, Architectural, and Environmental Engineering, Austin, TX, USA

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ABSTRACT

The risk of exposure to pollutants in mattress dust is enhanced by the extended period that people spend every day in their sleep microenvironments. Epidemiological studies have shown strong associations between exposure to these pollutants and health risks. Blankets, pillows, and mattresses have been considered as major sources of accumulated dust particles, which may become airborne through a process known as resuspension. Therefore, a better understanding of the impact of bedding arrangements on human-induced particle resuspension in the sleep microenvironment is needed. In this investigation, participants performed sets of prescribed movements on an artificially-seeded mattress. Ten different bedding arrangements were examined. Airborne particle number concentrations were measured to estimate size-resolved resuspension rates (RR). Across all particle sizes and bedding arrangements, RRs ranged from $10^{-3}$ *to* $10^{1}$ $h^{-1}$, with higher RRs associated with larger particles. RRs for a seeded pillow were greater than RRs for a seeded blanket or seeded mattress. The use of an additional pillow cover did act as an effective barrier to the penetration of larger particles deposited on the underlying pillow surface. Additionally, blankets were not found to be a significant barrier for particles resuspended from the underlying seeded mattress. Intake fractions (iF) were in the range of $10^{2}$ *to* $10^{4}$ ppm ($10^{-4}$ *to* $10^{-2}$ on a fractional basis), suggesting a significant fraction of released particles can reach the breathing zone region. The highest iF was estimated for an arrangement where both a pillow and a mattress were seeded without a blanket present ($10^{4}$ ppm).



## 1. Introduction

In developed countries, people spend about 90% of their time indoors [1,2]. Thus, exposure to indoor particulate and gaseous pollutants plays a significant role in affecting human health. Additionally, humans spend approximately one-third of their lives sleeping, typically on a mattress or other bedding material. Mattresses, pillows, bedding sheets, blankets, and duvet covers can be major sources of accumulated dust particles, which are dominated by particles smaller than 500 μm in effective diameter [3,4]. Furthermore, field studies have reported dust loads (not size resolved) measured on beds that range from 0.2 to 2.0 g $m^{-2}$ [3,5,6].

Settled mattress dust may contain a spectrum of pollutants, such as: house dust mite (HDM) allergens; bacteria; fungal spores; particle-bound semi-volatile organic compounds (SVOCs), e.g. flame retardants; fabric fibers; and detergent residue, e.g. zeolite particles [5,7–9]. The health risks associated with exposure to these pollutants in the sleep microenvironment are enhanced due to the close proximity of the mattress, pillow, and bedding to a person's airways [10]. Studies have shown that sensitization to HDM allergen is strongly associated with asthma [11,12]. It also has been shown that asthma symptoms in HDM-sensitized individuals are positively related to levels of HDMs in bed, but not to levels of HDMs on the bedroom floor [13,14].

Researchers have focused on the effect of daily vacuum-cleaning of the mattress to lower allergen levels [15–17]. HDM allergen levels can decrease significantly over an eight-week period of daily vacuuming [17]. Another study showed that vacuum cleaning of the mattress more than twice a year significantly lowers the HDM allergen levels [18]. Allergen-impermeable covers on pillows and

* Corresponding author. Danish Building Research Institute, Aalborg University, A.C. Meyers Vaenge 15, Copenhagen, Denmark. Tel.: +45 99 40 22 54.
*E-mail addresses:* mis@sbi.aau.dk, michal.spilak@gmail.com (M.P. Spilak), bboor@utexas.edu (B.E. Boor), atila@mail.utexas.edu (A. Novoselac), corsi@mail.utexas.edu (R.L. Corsi).

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**List of abbreviations**

| | |
|---|---|
| $A_{M,P}$ | seeded surface area ($m^2$); M-mattress, P-pillow |
| $V_c$ | volume of the experimental chamber ($m^3$) |
| $C_{i,BA}(t)$ | particle number concentration for particle size "$i$" in the bulk chamber air during movement set1 and set2 (#particles $m^{-3}$) |
| $C_{i,BA,CL}(t)$ | average particle number concentration for particle size "$i$" in the bulk chamber air during Clean set (#particles $m^{-3}$) |
| $\overline{C_{i,BZ}}$ | breathing zone particle number concentration for particle size "$i$" during movement routine on seeded mattress (# particles $m^{-3}$) |
| $\overline{C_{i,BZ,\ Decay}}$ | breathing zone particle number concentration for particle size "$i$" during decay period (# particles $m^{-3}$) |
| $C_{i,BZ,CL}(t)$ | breathing zone particle number concentration for particle size "$i$" during Clean set (#particles $m^{-3}$) |
| $L_{0,i}$ | initial mattress dust loading for particle size "$i$" (# particles $m^{-2}$) |
| $\overline{L_i}$ | average dust loading throughout the movement set for particle size "$i$" (# particles $m^{-2}$) |
| $L_i(t)$ | continuous mattress loading for particle size "$i$" (# particles $m^{-2}$) |
| $RR_i(t)$ | resuspension rate for particle size "$i$" throughout movement routine ($h^{-1}$) |
| $\overline{RR_i}$ | time-average resuspension rate for particle size "$i$" throughout the movement set ($h^{-1}$) |
| $Q_B$ | volumetric breathing rate ($m^3\ h^{-1}$) |
| $a$ | chamber air exchange rate ($h^{-1}$) |
| $k_i$ | particle deposition rate for particle size "i" ($h^{-1}$) |
| $iF_i$ | intake fraction for particle size "$i$" (ppm) |
| $\Delta t$ | instrument-specific sampling period (s) |

duvets have been recommended as a way of reducing exposure to allergens [19,20]. Bi-weekly washing of bedding in hot water (over 55 °C) has also been recommended for killing HDMs and removing a settled dust particles [21]. The particle-removal process of washing the bedding can be enhanced by using detergent or detergent with added bleach [21]. On the other hand, using detergents or bleach might lead to skin irritation [22,23].

There is limited research on individual bedding items and their contribution to the total concentration of pollutants in settled dust. Several studies analyzed the concentrations of HDM allergen in houses. Compared to allergen levels in pillows, Mills et al., 2002 [24] reported over a factor of two higher concentrations of allergens in duvets and a factor of four higher concentrations in mattresses.

Mattress foam may contain SVOCs such as flame retardants [25,26]. The amount of SVOCs present in the mattress foam and their emission rate is dependent on numerous factors, including the type of flame retardant, e.g., brominated or organophosphate, the type of foam, and environmental conditions. After being emitted from mattress foam, flame retardants may partition to settled particles and accumulate in mattress dust.

The resuspension of particulate matter from bedding surfaces has not been previously reported in the published literature. Resuspension is defined as a process by which deposited particles detach from a surface and become airborne by applying an external force or forces, e.g., aerodynamic (lift or drag), mechanical (surface vibrations and abrasion), and electrostatic [27]. Particle resuspension is influenced by numerous variables, including the strength of the external force, particle size, particle composition, surface features of the particle and deposition surface, characteristics of the airflow, dust load, and environmental parameters (e.g., relative humidity) [28–31]. The resuspension rate is usually not directly measured and is deduced through modeling based on a mass balance on the concentration of airborne and settled particles and deposition of the particles onto surfaces.

The objectives of this study were to explore the impact of bedding arrangements on resuspension and to evaluate exposure to resuspended particles in the sleep microenvironment. This study is the first to systematically evaluate human-induced particle resuspension from pillows, blankets, and mattresses during a sleep event and may serve as a basis for further evaluation of personal exposure to particles in sleep microenvironments.

## 2. Methods

### 2.1. Experimental setup

Thirty resuspension measurements were performed in a 14.75 $m^3$ chamber at The University of Texas at Austin. Three participants of different body mass and height were involved in this investigation (Table SI1 in the Supplemental Information (SI) section). Each participant wore a protective Tyvex suit with attached hoodie and boots (Model TY122 S, DuPont™), one-use respiratory mask (OSHA and NIOSH N95 rating, Model 8210, 3M™, USA) and single-use nitrile gloves. This protected participants from exposure during the measurements and helped to avoid contamination of particles accumulated on participant's clothing or skin which might interfere with the particle resuspension measurements. The bedding and duvet covers were washed after every use (standard wash cycle), allowed to air dry for a minimum of 48 h, and re-used again.

Polydisperse, 1–20 μm ISO-12103-1-A1 Ultrafine Arizona Test Dust (ATD) (Powder Technology Inc., USA) was used for the seeding procedure. The ATD size distribution is representative of particulate matter commonly found in mattress dust, e.g., fungal spores, bacteria or HDM allergens [3].

Both the experimental mattress and bedding arrangements were prepared and seeded with ATD in a custom-built, full-scale seeding chamber. The seeding chamber was built of extruded polystyrene panels with dimensions 1.2 × 2.1 × 1.4 m, and internally lined with aluminum foil to reduce electrostatic deposition. Six small mixing fans were placed inside the chamber in order to provide uniform mixing conditions during the injection process. The artificial dust was placed, and later injected, through six canisters attached to the removable top of the seeding chamber (canisters developed in Boor et al., 2013 [28]). The canisters were connected to a compressed air line with stable overpressure controlled by a ball valve. Every seeding process was performed with multiple releases of the highly-pressurized air to aerosolize the ATD contained in the canisters. The mixing fans, set to constant 10 V input, were stopped three minutes after the injection. The minimum period for particle deposition in the chamber was set as 24 h. The relative humidity and temperature in the seeding chamber were recorded for each seeding event (HOBO data logger, Model U12-012, HOBOware Pro, Onset Computer Co.).

Nine glass microscope slides were placed at different positions on the mattress (or pillow or blanket, depending on the particular arrangement) during the seeding process to determine the initial dust load and uniformity of deposited particles. The particle loading deposited on microscope slides was measured gravimetrically (Model AB 135-5, Meter-Toledo International Inc.) and was