Surrounded by a Cloud of Dust:
Particle Resuspension in Indoor Environments

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Workshop on The Health Risks of Indoor Exposure to Particulate Matter – February 10, 2016
"You know what I am? I'm a dust magnet!"¹

Human movements, activity patterns & occupancy

my Finnish neighbor's baby, Rolle

Big particulate(s) matter

$E$ for PM$_{10}$ due to walking* $\sim$ 1 to 10 mg/min

$\sim$ 10 to 100 kg of indoor dust particles $< 10$ $\mu$m resuspended in one's lifetime

*as surrogate for other activities, considering varying level of movement intensity: $E$ for 2-4 h, 0.1$E$ for 8 h, 0.01$E$ for 12-14 h, 78 y lifespan

Figure from: Qian, J. et al. (2014). Walking-Induced Particle Resuspension in Indoor Environments. *Atmos. Environ.* 89:464-481.
Resuspension = a source mechanism for all of the “stuff” in house dust

Exposure to resuspended particles

infants & the near-floor microenvironment: crawling, playing on carpet – little is known

the walking particle cloud: can induce self-exposure & exposure of others

mattress dust & the sleep microenvironment – 1/3rd of our life

occupational workplace exposures – contaminated clothing

Oh no, resuspended particles in my breathing zone!
From wind-blown dust to the mechanical foot: a timeline of seminal studies

Thatcher and Layton (1995): Haagen-Smit Prize

Nicholson (1993)

Wen and Kasper (1989)

Karlsson et al. (1999)

Corn and Stein (1965)

Montoya and Hildemann (2001)

Ferro et al. (2004)

Qian and Ferro (2008)

Rosati et al. (2008)

Mukai et al. (2009)

Gomes et al. (2007)

Ibrahim et al. (2003)

Tian et al. (2014)

Re-entrainment of Particles from a Plane Surface

Mechanistic approach – material-balance model

\[ V \frac{dC_j}{dt} = S_j - C_j(\beta_j V + Q) \]

\[ A \frac{dL_j}{dt} = C_j \beta_j V - S_j \]

source term, \( S_j \) (#/h)
emission rate: \( E_j \) (#/h) – not linked to dust
resuspension rate: \( RR_j L_j A - RR_j \) (h\(^{-1}\))
resuspension fraction: \( r_j L_j A f - r_j \) (-) \& \( f \) (movement frequency, h\(^{-1}\))
linking resuspension to exposure

Dust

Dust to air

Air to BZ

$E_j$, $RR_j$, $r_j$

$dN/d\log D_p$ & time
type of human movement
removal forces
occupancy

$L_j$ & volume fraction/$d\log D_p$
composition & morphology
deposit structure
adhesion
indoor surface

Vertical variation
airborne particle transport
airflow patterns
exposure assessment
linking resuspension to exposure

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**dust**

- $L_j$ & volume fraction/dlog$D_p$
- composition & morphology
- deposit structure
- adhesion
- indoor surface

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**dust to air**

- $E_j$, $RR_j$, $r_j$
- dN/dlog$D_p$ & time
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**air to BZ**

- vertical variation
- airborne particle transport
- airflow patterns
- exposure assessment

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**adult**

**infant**
Dust: need for size-resolved dust data from all indoor surfaces ($L_j$)

→ floor & mattress dust: commonly collected in epidemiological studies, e.g. analysis for SVOCs and microorganisms

→ little data on size distribution by number, volume/mass fraction, e.g. via laser diffraction, SEM

→ how does dust collection affect fragile agglomerates?

→ novel surface dust collection techniques

Dust loads on indoor surfaces (g/m$^2$): large variability

- hard floor: 0.1 to 10
- carpet: 1 to 100
- ventilation duct: 1 to 100
- mattress: 0.1 to 1
- clothing: ?

Note: above figure is for illustrative purposes and is not actual data
Dust: improving physical characterization of indoor dust

→ tools: microscopy, modeling
→ porosity: “cake-like” vs. “fluffy”
→ agglomeration of $< 10 \mu m$ particles
→ particle-surface & particle-particle interactions
→ formation over time
→ mass transfer of SVOCs within porous deposit?
→ how do we influence structure?, e.g.
  compression of carpet/fabric fibers, cleaning activities

Dust: considerations for biological particles & their adhesion to indoor surfaces

spectrum of shapes, surface features, aerodynamic diameters, electrostatic charge & extent of agglomeration/adhesion with other microbes in dust

- single bacterial cells ↔ bacterial agglomerates
- fungal spores ↔ fungal fragments
- pollen grains ↔ pollen fragments
- abiotic particle (e.g. mineral dust) with microbes attached

Dust: particles on fabric fibers (clothing, bedding), what do we know?


linking resuspension to exposure

- dust
  - dust to air
    - air to BZ
      - adult
      - infant
  - Lj & volume fraction/dlogDp
    - composition & morphology
    - deposit structure
    - adhesion
    - indoor surface
  - Ej, RRj, rj
    - dN/dlogDp & time
    - type of human movement
    - removal forces
    - occupancy
  - vertical variation
  - airborne particle transport
  - airflow patterns
  - exposure assessment
Dust to air: walking

Dust to air: walking – flooring type is key ($r_j$)

Figure from: Tian, Y. et al. (2014). A Comparative Study of Walking-Induced Dust Resuspension Using a Consistent Test Mechanism. *Indoor Air*. 24:592-603.

Image: http://i.imgur.com/POUMeTz.jpg?1
Dust to air: sleeping – experimental chamber study

routine of five movements, 10 volunteers, dust loads of 0.1 and 1 g/m²

Dust to air: sleeping – inhaling while sleeping

Mattress dust resuspension sequence

- 30 min. bkg.
- 12.5 min. movement
- 30 min. decay, no movement
- 12.5 min. movement
- 60 min. decay, no movement

Short-term concentration peak associated with movements M1-M5

Gradual elevation in concentration during movement routine

Dust loads
- 0.1 g/m²
- 1 g/m²
Dust to air: sleeping – resuspension rate ($RR_j$)

Data: 0.1 g/m², 2.9 h⁻¹, set 1, 10 volunteers
Dust to air: sleeping – the way you move ($RR_j$)

example: 3 to 5 µm

Movement Resuspension Rate, $RR_{Movement}$ (h$^{-1}$)

Set 1
- M1: sit on mattress
- M2
- M3
- M4
- M5

Set 2
- M1
- M2
- M3
- M4
- M5

0.1 g/m$^2$

M3: 360° rotation

M5: 180° rotation

M1: sit on mattress
Dust to air: clothing – Irish dancing to a Reel ($r_j$)


Dust to air: crawling – experimental chamber study

4 kg simplified mechanical crawling infant
real-time aerosol sampling in infant BZ and bulk air (not shown)
IOM inhalable sampler (~PM$_{100}$) for qPCR/NGS analysis

12 carpets borrowed from Helsinki residents
Dust to air: crawling – resuspension in real-time

video links:
https://vimeo.com/107277872
https://vimeo.com/107076687
Dust to air: crawling – “the infant playpen effect”

crawling path A – resuspension sequence
OPS in infant BZ

crawling path B – resuspension sequence
OPS in infant BZ

10 min. bkg., no crawl
10 min. crawl
15 min. decay, no crawl
10 min. bkg. no crawl
15 min. decay, no crawl

gravimetric calibration of OPS, $\rho \sim 1.4 \text{ g/cm}^3$
Dust to air: crawling – linking microbes in dust to infant BZ

large variation in microbial concentrations in infant BZ & surface dust across 12 + [5] = 17 carpets
analysis of qPCR data by Martin Täubel, Finnish National Institute for Health & Welfare

Spearman Correlation Coefficients
Penicillium/Aspergillus spp. group: 0.78
Cladosporium herbarum, Total Fungi & Gram-pos Bacteria: 0.43-0.59
Gram-neg Bacteria: 0.38
Dust to air: transient behavior – real-time bioaerosols

LIF: laser-induced fluorescence (UV-APS, WIBS, BioScout)
FBAP: fluorescent biological aerosol particle, $dN_F/d\log Dp$

Figure from: Bhangar, S. et al. (2014). Size-Resolved Fluorescent Biological Aerosol Particle Concentrations And Occupant Emissions in a University Classroom. *Indoor Air*. 24:604-617.
Dust to air: transient behavior – baby bot meets BioScout

BioScout operational principle:
- 405 nm excitation (Laser Diode)
- > 442 nm emission band
- 0.4 to 15.4 µm, 1 Hz

Dust to air: transient behavior – FBAPs: crawling vs. walking

10 min. bkg., no crawl
20 min. crawl
15 min. decay, no crawl

10 min. bkg., no walk
20 min. walk
15 min. decay, no walk
Dust to air: transient behavior – classifying bioaerosols in real-time

Dust to air: transient behavior – observing particle detachment w/ high speed imaging


linking resuspension to exposure

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**air to BZ**

vertical variation
airborne particle transport
airflow patterns
exposure assessment
Air to BZ: vertical variation – infants: the PIPER study

Air to BZ: vertical variation – the infant near-floor microenvironment

crawling path A – resuspension sequence
OPS in infant BZ & bulk air

10 min. crawl

10 min. bkg., no crawl

15 min. decay, no crawl

10 min. bkg. no crawl

15 min. decay, no crawl

crawling path B – resuspension sequence
OPS in infant BZ & bulk air

10 min. crawl

gravimetric calibration of OPS, $\rho \sim 1.4 \text{ g/cm}^3$

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**microbial group**

<table>
<thead>
<tr>
<th>microbial group</th>
<th>ratio of cell equivalents/m$^3$ in infant BZ to bulk air/adult BZ (mean, range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penicillium/Aspergillus spp. group</td>
<td>7.9 (4.1-13)</td>
</tr>
<tr>
<td>Total Fungi</td>
<td>9.4 (3.0-20)</td>
</tr>
<tr>
<td>Gram-pos bacteria</td>
<td>21 (4.8-47)</td>
</tr>
<tr>
<td>Gram-neg bacteria</td>
<td>13 (1.1-43)</td>
</tr>
<tr>
<td>PM$_{100}$ ($\mu$g/m$^3$)</td>
<td>4.6 (1.3-12)</td>
</tr>
</tbody>
</table>
Air to BZ: vertical variation – adults and their height

short > tall

Dust to Air to BZ: need for integrated measurements across all scales

Living Laboratories at Purdue CHPB

Small-Scale Wind Tunnel & Chamber Studies

Living Lab Office Space

ReNEWW Residential Test House at Purdue

Full-Scale Controlled Chamber Studies
Pigpen knows:
indoor particle resuspension
– a fascinating research
domain with many areas
remaining to be explored.
Acknowledgements

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Thank You!
Any Questions?