



Role of clothing in both accelerating and impeding dermal absorption of airborne SVOCs

Morrison, Glenn C.; Weschler, Charles J.; Bekö, Gabriel; Koch, Holger M.; Salthammer, Tunga; Schripp, Tobias; Toftum, Jørn; Clausen, Geo

Published in:
Journal of Exposure Science and Environmental Epidemiology

Link to article, DOI:
[10.1038/jes.2015.42](https://doi.org/10.1038/jes.2015.42)

Publication date:
2016

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Morrison, G. C., Weschler, C. J., Bekö, G., Koch, H. M., Salthammer, T., Schripp, T., Toftum, J., & Clausen, G. (2016). Role of clothing in both accelerating and impeding dermal absorption of airborne SVOCs. *Journal of Exposure Science and Environmental Epidemiology*, 26(1), 113-118. <https://doi.org/10.1038/jes.2015.42>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

1
2
3 1 **Title:** Role of clothing in both accelerating and impeding dermal absorption of airborne
4
5 2 SVOCs
6
7
8 3
9

10 4 **Authors:** Glenn C. Morrison, PhD¹, Charles J. Weschler, PhD^{2,3}, Gabriel Bekö, PhD³, Holger
11
12 5 M. Koch, PhD⁴, Tunga Salthammer, PhD⁵, Tobias Schripp, PhD⁵, Jørn Toftum, PhD³ and Geo
13
14 6 Clausen, PhD³
15
16
17
18 7
19

20 8 **Affiliations:**
21

22 9 ¹ Civil, Architectural and Environmental Engineering, Missouri University of Science and
23
24 10 Technology, Rolla, MO, 65409, USA
25
26

27 11 ² Environmental and Occupational Health Sciences Institute, Rutgers University, 170
28
29 12 Frelinghuysen Road, Piscataway, NJ 08854, USA
30
31

32 13 ³ International Centre for Indoor Environment and Energy, Department of Civil
33
34 14 Engineering, Technical University of Denmark, DK-2800, Lyngby, Denmark
35
36

37 15 ⁴ Institute for Prevention and Occupational Medicine of the German Social Accident
38
39 16 Insurance, Institute of the Ruhr-Universität Bochum (IPA), Bürkle-de-la-Camp-Platz 1,
40
41 17 44789 Bochum, Germany
42
43

44 18 ⁵ Fraunhofer WKI, Department of Material Analysis and Indoor Chemistry, Bienroder Weg
45
46 19 54E, 38108 Braunschweig, Germany
47
48
49 20

50
51 21 **Address correspondence to:** Glenn Morrison, Civil, Architectural and Environmental
52
53 22 Engineering, Missouri University of Science and Technology, Rolla, MO, USA.
54
55

56 23 Telephone: 573-341-7192. Fax: 573-341-4729. E-mail: gcm@mst.edu.
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

24

25 **Running title:** Clothing enhances dermal uptake of airborne SVOCs

26

27 **Competing financial interests:** All authors declare no actual or potential competing
28 financial interests.

29

30

For Peer Review Only

1
2
3 314
5
6 32 **Abstract**

7
8 33 To assess the influence of clothing on dermal uptake of SVOCs, we measured uptake of
9
10 34 selected airborne phthalates for an individual wearing clean clothes or air-exposed clothes
11
12 35 and compared these results with dermal uptake for bare-skinned individuals under
13
14 36 otherwise identical experimental conditions. Using a breathing hood to isolate dermal from
15
16 37 inhalation uptake, we measured urinary metabolites of diethylphthalate (DEP) and di-n-
17
18 38 butylphthalate (DnBP) from an individual exposed to known concentrations of these
19
20 39 compounds for 6 hours in an experimental chamber. The individual wore either clean
21
22 40 (fresh) cotton clothes or cotton clothes that had been exposed to the same chamber air
23
24 41 concentrations for 9 days. For a 6-hour exposure, the net amounts of DEP and DnBP
25
26 42 absorbed when wearing fresh clothes were respectively 0.017 and 0.007 $\mu\text{g}/\text{kg}/(\mu\text{g}/\text{m}^3)$;
27
28 43 for exposed clothes the results were 0.178 and 0.261 $\mu\text{g}/\text{kg}/(\mu\text{g}/\text{m}^3)$ (values normalized
29
30 44 by air concentration and body mass). When compared against the average results for bare-
31
32 45 skinned participants, clean clothes were protective, while exposed clothes increased
33
34 46 dermal uptake for DEP and DnBP by factors of 3.3 and 6.5 respectively. Even for non-
35
36 47 occupational environments, wearing clothing that has adsorbed/absorbed indoor air
37
38 48 pollutants can increase dermal uptake of SVOCs by substantial amounts relative to bare
39
40 49 skin.

41
42
43
44
45
46
47
48
49 50 **Introduction**

50
51 51 Dermal absorption of organic compounds directly from air has been observed for some
52
53 52 volatile and semi-volatile compounds. In reviews by Rehal et al.¹ and Rauma et al.² a
54
55 53 handful of volatile organic compounds (VOCs) have been observed to have dermal uptakes
56
57
58
59
60

1
2
3 54 that are substantial compared to inhalation intakes. For example, Piotrowski^{3,4} found that
4
5 55 nitrobenzene and phenol doses via dermal absorption were about 50% those due to
6
7
8 56 absorption by inhalation. Weschler and Nazaroff^{5,6} argued that the dermal absorption dose
9
10
11 57 from air could also compare with or exceed the dose due to inhalation for semi-volatile
12
13 58 organic compounds (SVOCs) that meet specific criteria under steady-state conditions. In a
14
15 59 refinement of that model for non-steady-state conditions, Gong et al.⁷ showed that timing of
16
17
18 60 exposure can significantly influence dose due to resistance and accumulation within the
19
20
21 61 dermis. In a test of the hypothesis that the dermal dose of SVOCs from air could be
22
23 62 significant, Weschler et al.⁸ showed that dermal absorption was approximately equal to
24
25 63 inhalation dose for six bare-skinned male participants exposed to diethylphthalate (DEP)
26
27
28 64 and di n-butylphthalate (DnBP) for six hours in a chamber.
29

30 65
31
32 66 A few studies have evaluated how clothing may influence dermal uptake of organic
33
34
35 67 compounds from air or by transfer from treated fabrics. Piotrowski³ found that clothing
36
37 68 reduced dermal uptake of airborne nitrobenzene by about 20-30% but had no observable
38
39
40 69 effect on phenol absorption.⁴ Organics that have been applied to clothing can be also
41
42 70 absorbed. Blum et al.⁹ observed metabolites of a flame retardant in the urine of children
43
44
45 71 who had worn clothing treated with this flame retardant. Similarly, subjects wearing
46
47 72 permethrin-impregnated battle dress uniforms absorbed this insecticide as evidenced by
48
49 73 urinary metabolites¹⁰⁻¹².

50
51 74
52
53
54 75 We hypothesize that sorption to clothing acts either to reduce or to increase dermal
55
56 76 uptake, depending on the extent to which the clothing has equilibrated with room air
57
58
59
60

1
2
3 77 contaminants prior to wearing. For some compounds, the boundary layer of air adjacent to
4
5 78 the skin presents greater resistance to transport than does the stratum corneum and viable
6
7
8 79 epidermis.⁶ For such compounds uptake is sensitive to the magnitude of the boundary layer
9
10
11 80 permeability⁷ and could be altered significantly by sorption to fabrics, especially for
12
13 81 compounds with high air-fabric partition coefficients.
14

15
16 82
17
18 83 For fabrics that are initially clean, adsorption to fabric fibers should decrease fabric
19
20 84 permeability, and lower overall dermal uptake, by reducing diffusional flux through the
21
22 85 fabric. With continued exposure, fabric permeability would increase as fabric surfaces
23
24 86 equilibrate with SVOCs. Fabrics that are exposed to building air for extended periods (e.g.
25
26 87 hanging up in a closet) may absorb a substantial quantity of SVOCs, or even reach
27
28 88 equilibrium, prior to wearing. For these clothes, we predict that dermal uptake will be
29
30 89 higher than uptake to bare skin.
31
32
33
34

35 90
36
37 91 Our objective is to test this hypothesis with two compounds that have been predicted, and
38
39 92 recently shown, to exhibit low dermal uptake resistance relative to mass-transfer
40
41 93 resistance through the layer of air adjacent to body surfaces. In this study, we measure
42
43 94 urinary concentrations and total excretion of DEP and DnBP metabolites during and after a
44
45 95 participant is exposed for 6 hours to known air concentrations of DEP and DnBP for 2
46
47 96 conditions: i) wearing freshly cleaned cotton clothing; ii) wearing previously clean cotton
48
49 97 clothing that had been exposed to the phthalates for at least one week. Inhalation uptake is
50
51 98 controlled with a breathing hood. Results are compared against results from six individuals
52
53
54
55
56
57
58
59
60

1
2
3 99 who wore only shorts but were subjected to nearly identical conditions (results reported in
4
5
6 100 Weschler et al.⁸).

7
8 101

9
10 102 **Methods**

11
12
13 103 The experiments reported here were integrated into the dermal uptake experiments
14
15 104 reported by Weschler et al.⁸ and nearly all procedures, conditions and analytical methods
16
17 105 are therefore identical. The clothed individual was exposed to phthalates in the same
18
19 106 chamber at the same time as bare-skinned participants during two of the chamber
20
21 107 exposure intervals, specifically Wednesday of the 1st week and Tuesday of the 2nd week.
22
23 108

24
25
26
27 109 *Exposure chamber*

28
29
30 110 The 55 m³ chamber housed two mixing fans, desks and chairs. The air exchange rate was
31
32 111 maintained at 0.7 1/h and the temperature was controlled at 30°C. The relative humidity
33
34 112 was not controlled and ranged from 20 to 35% during the experiments. A breathing hood
35
36 113 (Amron International, Vista, CA, #8890 Oxygen Treatment Hood) was used so that the
37
38 114 participant in the clothing experiments could breathe clean air from outside the chamber,
39
40 115 thus allowing for the separation of dermal from inhalation dose. See Figure S.1 for an image
41
42 116 of the participant wearing test clothing and the hood while seated in the experimental
43
44 117 chamber. Air concentrations of DEP and DnBP were maintained by continuous emission
45
46 118 from aluminum panels (total area of 12 m²) coated with Latex paint. The paint had been
47
48 119 formulated with 1% DEP and 10% DnBP (by weight), and was used to deliver these
49
50 120 phthalates into chamber air at a relatively constant emission rate.^{8,13}
51
52
53
54
55

56 121
57
58
59
60

1
2
3 122 *Clothing and clothing preparation*
4

5
6 123 Clothing was purchased from two different clothing stores in Rolla, Missouri, USA. Each set
7
8 124 included a cotton undershirt, a pair of cotton jeans, a long-sleeved cotton tee shirt, cotton
9
10 125 underwear and cotton socks. Details such as size, style and manufacturer can be found in
11
12
13 126 Table S.1.
14

15 127
16
17
18 128 Two sets of clothing were prepared by washing all pieces at the same time in a standard
19
20 129 clothes washer using unscented detergent. They were then dried in an electric dryer on the
21
22 130 “medium” setting and each set was packaged separately in two layers of clean aluminum
23
24 131 foil until use. During the first 6-hour exposure period, one set was worn directly from its
25
26 132 package and is denoted “fresh”. Another set of clothing was exposed to chamber air for 9
27
28 133 days and denoted as “exposed”. This exposure took place in the same chamber, under the
29
30 134 same conditions and at the same time as bare-skin dermal uptake experiments occurred;
31
32 135 the latter are described in Weschler et al.⁸ The clothing was hung inside-out in the path of
33
34 136 fans to improve transfer of phthalates from air to the clothing. The air concentration was
35
36 137 measured during days 2 and 3 of the 9 day clothing-exposure interval. During these
37
38 138 periods, the average concentrations for DEP were 250 and 233 $\mu\text{g}/\text{m}^3$ and that of DnBP
39
40 139 was 123 and 114 $\mu\text{g}/\text{m}^3$.
41
42
43
44
45
46

47 140
48
49 141 *Preparation of participant*
50

51
52 142 Because there were a limited number of breathing hoods available in the exposure
53
54 143 chamber, it was only possible to study one clothed participant. The participant was a 48
55
56 144 year old Caucasian male, 192 cm tall weighing 91 kg. The participant followed the same
57
58
59
60

1
2
3 145 restricted diet and restricted use of personal care products protocol described in Weschler
4
5
6 146 et al.⁸ These restrictions were intended to reduce background metabolites of DEP and
7
8 147 DnBP in the participants' urine. In brief, for 12 hours prior to exposure and 54 hours after
9
10 148 exposure began, the participant only ate Swedish dried bread and ate thick-rinded fruit
11
12
13 149 such as oranges, bananas and melons. He drank only tap water or tea made from tap water.
14
15 150 The participant showered without soaps or detergents 24 hours prior to the experiment
16
17
18 151 and showered without soaps again 48 hours after the beginning of an exposure. The
19
20 152 research protocol was approved by the Capital Region of Denmark Committee for Research
21
22
23 153 Ethics. The participant provided informed consent before participation and consented to
24
25 154 publication of his photo.
26
27
28 155

29
30 156 *Description of exposure periods*

31
32 157 The participant participated in two exposure experiments. The first took place on a
33
34 158 Wednesday coincident with the 2nd set of exposure experiments during the first week
35
36
37 159 described in Weschler et al.⁸ The participant collected two urine samples on the morning of
38
39 160 the experiment. Immediately before entering the chamber the participant collected a urine
40
41 161 sample, changed into the "fresh" set of experimental clothes, donned a breathing hood and
42
43 162 entered the chamber at 11:00. The participant sat at a desk for most of the 6-hour exposure
44
45 163 period and left the chamber once briefly to collect a urine sample. At 17:00, the participant
46
47 164 left the chamber and changed into his normal clothing. Following this, the participant
48
49 165 maintained the restricted diet and personal product restrictions and collected all urine for
50
51
52 166 48 hours. The second exposure experiment took place on a Tuesday coincident with the 3rd
53
54
55 167 set of exposure experiments during the second week described in Weschler et al.⁸ The
56
57
58
59
60

1
2
3 168 procedure was identical to the first experiment except that the participant changed into the
4
5
6 169 “exposed” set of clothes before entering the chamber at 10:00 (leaving at 16:00).
7

8 170
9

10
11 171 *Analysis of air and urine*
12

13 172 Air concentrations of phthalates were determined by first collecting 6 L samples of air with
14
15 173 Tenax-TA filled thermal desorption tubes, and analyzing by thermal desorption followed by
16
17 174 gas chromatography using a mass selective detector. Phthalates were quantified using
18
19
20 175 original standards. The concentrations in air and other conditions are tabulated in
21
22
23 176 Weschler et al.⁸
24

25 177
26

27 178 Urine samples were weighed on the day of collection and stored in a freezer until they were
28
29
30 179 shipped overnight to the Institute for Prevention and Occupational Medicine of the German
31
32 180 Social Accident Insurance in Bochum, Germany. Urine samples were analyzed for mono-
33
34 181 ethyl phthalate (MEP), a metabolite of DEP, as well as mono-n-butyl phthalate (MnBP) and
35
36
37 182 3OH-mono-n-butyl phthalate (3OH-MnBP), metabolites of DnBP. The concentrations of
38
39
40 183 these metabolites were determined by two-dimensional high performance liquid
41
42 184 chromatography coupled to tandem mass spectrometry (LC/LC-MS/MS) using internal
43
44 185 isotope-labeled standards after enzymatic deconjugation of the phthalate metabolites from
45
46 186 the glucuronidated form following methods published by Koch et al.^{14,15} Other details of
47
48
49 187 analytical methods can be found in Weschler et al.⁸
50

51 188
52

53
54 189 *Calculations*
55
56
57
58
59
60

1
2
3 190 Calculated total uptake of DEP or DnBP during the 6 hour exposure period was based on
4
5
6 191 methods described by Koch et al.¹⁵⁻¹⁷ and outlined in Weschler et al.⁸ Metabolite
7
8 192 concentrations were converted to mass excreted and then converted to parent molecule
9
10 193 uptake using predetermined metabolic conversion factors. In the “fresh clothes”
11
12 194 experiment there was very low overall dermal uptake of DEP and DnBP (see Results and
13
14 195 Discussion). To better quantify uncertainty in this case, background uptake has been
15
16 196 determined in a somewhat different manner than in Weschler et al.⁸ For the present
17
18 197 participant, little residual uptake from the 6-hour experiment remained, relative to
19
20 198 background uptake, for the last four urinations of the fresh clothes experiment (collected
21
22 199 from 40.5 to 50.0 hours after exiting the chamber). Therefore, the average dose rate (total
23
24 200 dose/elapsed time) from these samples was subtracted from the dose rate calculated for
25
26 201 each post-exposure sample for both fresh and exposed clothes experiments. This was
27
28 202 multiplied by the sample time interval, and the result from each interval summed, to
29
30 203 determine the background-corrected total dose. Dermal uptake was also corrected for DEP
31
32 204 and DnBP measured in the breathing hood air ($40.7 \mu\text{g}/\text{m}^3$ and $5.7 \mu\text{g}/\text{m}^3$, respectively)
33
34 205 using a breathing rate of $0.7 \text{ m}^3/\text{h}$. Dermal uptake was then normalized by the air
35
36 206 concentration during the 6 hours in the chamber and the participant’s weight. Also
37
38 207 reported is the average flux for the 6-h exposure, corrected for background uptake and
39
40 208 hood air inhalation. Exposed surface area is taken as 2.06 m^2 , estimated by equation 7A-7
41
42 209 of the Exposure Factors Handbook¹⁸ and corrected for the area of the head (6.6% of total).
43
44 210 To compare the rate of uptake among exposure conditions and between phthalates, we
45
46 211 calculated a normalized metabolite excretion rate. First we calculated the slope of net
47
48 212 metabolite vs time from initial sample (after exposure begins) to the last sample that
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 213 includes no more than 75% of total net metabolite excreted. This slope divided by the total
4
5
6 214 mass excreted was defined as the normalized metabolite excretion rate. See Table S.2 for
7
8 215 additional details regarding the calculation methods.
9

10 216

11 12 13 217 **Results and Discussion**

14
15 218 Major quantitative results are shown in Table 1. There is a striking difference between
16
17
18 219 results for fresh and exposed clothing experiments. The net metabolites excreted over the
19
20 220 54 hour period after initiation of exposure are far higher for exposed clothes than for fresh
21
22 221 clothes, indicating that parent compound uptake is much higher for exposed than for fresh
23
24
25 222 clothes. When corrected for background uptake rate and inhalation from the breathing
26
27 223 hood and normalized by body mass and air concentration, wearing exposed clothes
28
29
30 224 resulted in DEP and DnBP uptakes that were 11 and 36 times greater, respectively, than
31
32 225 when wearing fresh clothes. The mass of metabolites excreted over the first 24 hours by
33
34 226 the volunteer wearing exposed clothes (3.6 mg MEP; 2.1 mg MnBP) approaches that due to
35
36
37 227 application of a 2% DEP/DnBP cream over most of the skin of subjects as reported by
38
39 228 Janjua et al.¹⁹ (MEP range 2.5-85 mg; MnBP range 3.6-18 mg).
40

41 229

42
43
44 230 The ratio of the normalized uptake of DEP/DnBP was very different for the two scenarios.
45
46 231 For exposed clothing, normalized uptake of DEP is somewhat smaller than for DnBP
47
48 232 (DEP/DnBP = 0.7), but for fresh clothing it is much higher (DEP/DnBP = 2.3). This suggests
49
50 233 that fresh clothes retard uptake of DnBP more than DEP and/or that exposed clothes
51
52
53 234 enhance uptake of DnBP relative to DEP. Both mechanisms are consistent with a higher
54
55
56 235 cloth/air partition coefficient for DnBP, which has a higher molecular weight than DEP.
57
58
59
60

1
2
3 236
4
5
6 237 Normalized dermal uptake for both fresh and exposed clothes differ substantially from
7
8 238 uptake to bare skin as described in Weschler et al.⁸ For comparison, results for bare skin
9
10 239 and clothing experiments are shown in Figure 1. For exposed clothes, normalized uptake of
11
12 240 DEP and DnBP are 3.3 and 6.5 times greater, respectively, than the average of bare skin
13
14 241 results and 1.9 and 3.9 times higher than the highest uptake observed in the bare skin
15
16 242 experiments. For fresh clothes, uptake is 3.2 and 5.6 times lower than the average for bare
17
18 243 skin experiments. Based on a t-test, the probability, p , of the results stemming from random
19
20 244 variation was $<10^{-4}$ for exposed clothes and <0.017 for fresh clothes. These findings are
21
22 245 consistent with the hypothesis that fresh clothes retard uptake and exposed clothes
23
24 246 increase uptake compared with bare skin.
25
26
27
28
29

30 247
31
32 248 A comparison of the results, accounting for participant age, is also enlightening. Weschler
33
34 249 et al.⁸ observed a striking relationship between dermal uptake and age. Shown in Figure 2a
35
36 250 and 2b are plots of net amounts of MEP and MnBP excreted, from the time exposure began
37
38 251 until the end of urine sampling, for the two clothing experiments (worn by a 48 year-old
39
40 252 participant) and bare skin results from the 47 year-old participant reported by Weschler et
41
42 253 al.⁸ For both phthalates, wearing exposed clothing increased the excretion rate and net
43
44 254 excretion by a large margin. Wearing fresh clothes significantly reduced excretion rate and
45
46 255 net excretion.
47
48
49
50

51 256
52
53
54 257 In Figure 3, normalized clothing results for uptake of parent compounds are plotted against
55
56 258 age along with the normalized results for all six bare-skinned participants. The clothing
57
58
59
60

1
2
3 259 results are clearly “off the line”; the exposed clothes result in much higher uptake and fresh
4
5
6 260 clothes much lower uptake than for bare skin. Again, using the 47 year-old participant from
7
8 261 Weschler et al.⁸ as the best comparator, we observe that exposed clothes resulted in 2.3
9
10 262 and 3.4 times more uptake of DEP and DnBP respectively. Fresh clothes resulted in 4.5 and
11
12 263 11 times lower uptake.

14
15 264

17
18 265 The excretion rate of metabolites differs among conditions and between phthalate
19
20 266 metabolites. The difference between MnBP and MEP is apparent for exposed clothes in
21
22 267 Figure 2, with MEP rising faster than MnBP. The normalized excretion rate for both
23
24 268 conditions studied in this research and for the six bare skin participants is shown in Figure
25
26
27 269 4. To make the comparison more clear, the bare skin results for participants wearing
28
29 270 hoods are grouped with the clothed results. Qualitatively, clothed results are similar to
30
31 271 bare skin results: the normalized excretion rate of MEP is higher than for MnBP. For both
32
33 272 MEP and MnBP, the excretion rate is higher for exposed clothes than for fresh clothes. This
34
35 273 is consistent with the hypothesis that fresh clothes act as a barrier and delay transport
36
37 274 from air to skin. The difference is more pronounced for MnBP than for MEP, possibly due to
38
39 275 stronger sorption of DnBP to clothing.

41
42 276

43
44 277 The results support the hypotheses that 1) fresh clothes are protective, reducing uptake of
45
46 278 DEP and DnBP compared with bare-skinned participants and 2) exposed clothes increase
47
48 279 uptake. Although only one participant was tested (in two exposure periods), we believe the
49
50 280 results are compelling, especially when compared with the narrow range of results for six
51
52 281 bare-skinned participants. All results are significantly different from the six bare-skinned
53
54
55
56
57
58
59
60

1
2
3 282 participant results. When compared by age, the difference is even more apparent (Figure
4
5
6 283 3). However, replication of these results with a larger number of participants will be
7
8 284 valuable.

9
10 285
11
12
13 286 For both DEP and DnBP, the dose while wearing fresh clothes is small and could have come
14
15 287 from a combination of penetration through clothing and absorption by bare skin. The
16
17 288 participant in this study was not completely clothed: the hands were bare. We can estimate
18
19
20 289 the absorbed dose by hands assuming that hands are 4.7% of an average adult male's total
21
22 290 surface area.¹⁸ We will use participant 2, the bare skinned participant closest in age to the
23
24
25 291 clothed participant, for comparison and will assume that the shorts worn by participant 2
26
27 292 covered approximately 5% of his total surface area. Correcting for the reduced total
28
29
30 293 exposed area due to hood (3.9% of total surface area) and shorts, the normalized dermal
31
32 294 uptake due to exposed hands for participant 2 would be approximately 0.004 and 0.003
33
34 295 $\mu\text{g}/\text{kg} / (\mu\text{g}/\text{m}^3)$ for DEP and DnBP respectively. These values can be compared with 0.017
35
36 296 and 0.007 $\mu\text{g}/\text{kg} / (\mu\text{g}/\text{m}^3)$ for DEP and DnBP for the fresh clothes experiment. Hence, for
37
38
39 297 DnBP, uptake by bare hands could represent a substantial fraction of total uptake from the
40
41
42 298 fresh clothing experiment. It is also interesting to note that the estimated DEP uptake by
43
44 299 bare hands accounts for only 25% of the observed uptake; therefore, penetration through
45
46
47 300 clothing may account for much of the uptake.

48
49 301
50
51
52 302 It is perhaps intuitive that fresh clothes should impede transfer from air to skin of airborne
53
54 303 contaminants. Clothing has been designed to protect workers from pesticide spray and
55
56 304 industrial toxic gases. A recent paper reported on the ability of "every-day" clothing²⁰ to
57
58
59
60

1
2
3 305 reduce in vitro dermal penetration of chlorpyrifos from solution. But early human subject
4
5
6 306 studies of VOCs showed little influence of clothing on dermal absorption of nitrobenzene
7
8 307 and phenol.^{3,4} This could be because sorption to cloth is weak for these low molecular
9
10 308 weight compounds. Higher molecular weight, low volatility organic compounds are known
11
12 309 to exhibit substantial air-fabric partitioning.^{21,22} As volatility decreases, partitioning from
13
14 310 air to fabric increases and we would anticipate that retardation of transport across fabric
15
16 311 would also increase. Indeed, in this research we observed a lower normalized uptake of
17
18 312 DnBP relative to DEP, consistent with the roughly 25 times lower vapor pressure of DnBP.
19
20
21
22 313
23
24 314 Given the complicated geometry of fabric and skin, and the potential for air movement
25
26 315 through and under fabric, the data cannot be used to test more detailed models, to generate
27
28 316 exposure estimates or to identify compound/fabric combinations that would be most
29
30 317 protective or hazardous. Qualitatively, the transport of SVOCs into and out of clothing may
31
32 318 be described well by a model of transport of contaminants through porous media.²³ In the
33
34 319 context of this model, both advection and diffusion of contaminants through fabric would
35
36 320 be retarded by sorption. Key parameters influencing transport and dermal uptake are
37
38 321 likely to include the geometry and permeability of the fabric, how closely clothing fits, the
39
40 322 air-to-cloth partition coefficient, the dermal permeability of the contaminant, the elapsed
41
42 323 time the cloth is exposed to contaminated air after washing and the elapsed time clothing is
43
44 324 worn.
45
46
47
48
49
50
51
52
53

54 326 **Geometry and permeability of fabric.** Transport of air and moisture through fabric has
55
56 327 been extensively measured and modeled.²⁴⁻²⁷ Hydraulic permeability lumps geometric
57
58
59
60

1
2
3 328 complexity of fabric into a parameter that characterizes fabric resistance to advective flux;
4
5
6 329 hydraulic permeability is defined as the volume flux of air due to a specific pressure
7
8 330 difference across the fabric in units of $\text{cm}^3/(\text{cm}^2 \text{ s})$ (usually at a pressure difference equal
9
10
11 331 to 125 Pa). Hydraulic permeability can range over several orders of magnitude: very low
12
13 332 ($<0.1 \text{ cm}^3/(\text{cm}^2 \text{ s})$) for dense or sealed materials and very high for loosely woven thin
14
15 333 fabrics ($>300 \text{ cm}^3/(\text{cm}^2 \text{ s})$). SVOC transport is likely to be more influenced by advection in
16
17
18 334 loosely woven materials with a high hydraulic permeability; for tightly woven materials,
19
20 335 diffusive transport is expected to dominate. For intermediate materials, the relative
21
22
23 336 contributions of diffusion and advection will be influenced by pressure gradients, wind and
24
25 337 movement.

26
27 338
28
29
30 339 **How close clothing fits.** Some sorbed SVOCs may transfer from cloth to skin by contact.
31
32 340 However, since most of the surface area available for adsorption in a woven fabric is
33
34 341 internal, only a small fraction of the sorbed SVOC is likely a consequence of transfer by
35
36
37 342 direct contact with the outer fabric fibers. Instead, we believe that the more important
38
39 343 mechanism is desorption from fiber surfaces and diffusion across a thin air gap to skin. For
40
41
42 344 diffusion across a quiescent air gap, flux is proportional to the reciprocal of the air gap
43
44 345 distance. The air gap distance was not measured in this study but we estimate it ranged
45
46 346 from $<0.1 \text{ cm}$ to 0.5 cm . By comparison, a typical bare-skin concentration boundary layer is
47
48
49 347 about 0.2 to 0.4 cm , which can be estimated by dividing the gas diffusivity of the SVOC
50
51 348 ($0.056 \text{ cm}^2/\text{s}$)²⁸ by an air-to-skin deposition velocity (0.14 - 0.28 cm/s)²⁹. Therefore, the
52
53
54 349 initial flux from fabric to skin could be smaller, or more than 4 times greater, than from
55
56 350 bulk air when wearing equilibrated clothing. Notably, this estimate overlaps the observed
57
58
59
60

1
2
3 351 ratio of uptake for exposed clothing to the average for bare skin (3.3 for DEP and 6.5 for
4
5 352 DnBP).
6
7
8 353

9
10 354 **Air-to-cloth partitioning.** The sorptive capacity of fabric will influence how it reduces or
11
12 355 enhances transport from air to skin. There is recognition that adsorption and desorption of
13
14 356 indoor-relevant gases on fabrics for tobacco smoke products³⁰⁻³² and pesticides²¹ can
15
16 357 influence exposure. Several studies have shown that dry-cleaning solvents³³⁻³⁶ and moth
17
18 358 repellants³⁷ can sorb to clothing and subsequently desorb, increasing indoor
19
20 359 concentrations. Specialty fabrics have been developed that sorb or react with chemical
21
22 360 warfare agents or pesticides to protect the wearer.³⁸ However, we have only identified two
23
24 361 papers^{22,39} that report equilibrium partition coefficients for an indoor air contaminant and
25
26 362 commonly worn fabrics. In one paper²² the investigators measured equilibrium partition
27
28 363 coefficients for airborne free-base methamphetamine and fabrics including cotton and
29
30 364 polyester. The partition coefficients were high enough that mouthing of these fabrics was
31
32 365 predicted to be the primary route of exposure for toddlers, similar to the observation by
33
34 366 Gurunathan et al.²¹ for chlorpyrifos and plush toys.
35
36
37
38
39
40
41
42
43

44 368 **Dermal permeability.** We anticipate that the compounds that are most likely to exhibit
45
46 369 enhanced dermal uptake from exposed clothes are those that have high dermal
47
48 370 permeability coupled with gas-to-fabric partition coefficients in an intermediate range (not
49
50 371 too high, not too low). Uptake of compounds with low dermal permeability is limited by
51
52 372 resistance across skin; modest changes in mass-transfer conditions external to skin will
53
54 373 likely have little impact on overall uptake. Dermal permeability of compounds typical of
55
56
57
58
59
60

1
2
3 374 indoor air have been estimated by Weschler and Nazaroff.⁶ They identified more than 30
4
5 375 common indoor pollutants that are predicted to have high dermal uptake relative to
6
7
8 376 inhalation uptake. If a compound has too high a gas-to-fabric partition coefficient, this will
9
10 377 retard transfer from the fabric to skin. On the other hand, if a compound has too small a
11
12 378 gas-to-fabric partition coefficient, then exposed clothes have sorbed very little of the
13
14 379 compound and there will be concomitantly little enhancement. It is in the intermediate
15
16 380 range of gas-fabric partitioning that sorption to clothes prior to wear will have the greatest
17
18 381 enhancement on uptake.
19
20
21
22
23
24

25 383 **Elapsed time clothing sorbs contaminants and time clothing is worn.** It takes time for
26
27 384 fabric to adsorb airborne contaminants and approach equilibrium with gas phase
28
29 385 concentrations. It also takes time for contaminants to desorb and transfer to skin. As an
30
31 386 example, consider a tight-fitting shirt that has been washed, stored in the presence of a
32
33 387 contaminant (in air) and then worn. If we assume that the characteristic time for the fabric
34
35 388 to equilibrate (τ_e) is independent of the air concentration, then we can qualitatively
36
37 389 compare this time to the actual time stored in the presence of a contaminant (t_s) or the time
38
39 390 clothing is worn after storage (t_w). *Scenario 1: $t_s < \tau_e$.* For this scenario, the fabric has not
40
41 391 equilibrated with the contaminant concentration in the air and may in fact continue to sorb
42
43 392 contaminants even while worn. Regardless of the chemical, enhanced flux from cloth to
44
45 393 skin will be limited. *Scenario 2: $t_s \geq \tau_e$ and $t_w < \tau_e$.* For this scenario the fabric is well
46
47 394 equilibrated with a contaminant before wearing, but the time worn is short relative to the
48
49 395 time it takes for the contaminant to reach a new steady-state. During the time worn, flux to
50
51 396 skin will be enhanced but the mass adsorbed to fabric will not change substantially. This
52
53
54
55
56
57
58
59
60

1
2
3 397 scenario could be represented by a shirt worn for a short time that had adsorbed a
4
5
6 398 relatively more volatile, low partition coefficient chemical; it could also be represented by a
7
8 399 shirt worn for a longer period of time that had adsorbed a less volatile, higher partition
9
10 400 coefficient chemical. *Scenario 3*: $t_s \geq \tau_e$ and $t_w > \tau_e$. Here, the shirt has been worn long enough
11
12 401 that a substantial fraction of the contaminant has desorbed. While the initial flux to skin
13
14 402 may be high, the time-averaged flux will be lower than for *Scenario 2* (all else being equal).
15
16
17
18 403

19
20 404 Since DnBP is anticipated to have a higher partition coefficient than DEP, we would
21
22 405 anticipate that τ_e would be greater for DnBP than DEP. We observe a normalized dermal
23
24 406 uptake that is higher for DnBP than DEP from exposed clothes. If the 6-hour period that the
25
26 407 participant wears the exposed clothing is similar or longer than τ_e for DEP, then it may fall
27
28 408 under *Scenario 3*, while DnBP falls under *Scenario 2*.
29
30
31
32
33 409

34 35 410 **Conclusions**

36
37 411 Clothing acts as a barrier to exposure, but also as a reservoir for recently adsorbed
38
39 412 chemicals; the latter can increase dermal uptake. Not only are people subjected to airborne
40
41 413 SVOCs while at home, they are also exposed to “home pollutants” outside of their residence
42
43 414 when they wear clothing that has been stored in the presence of various SVOCs at home.
44
45 415 Given the very large increase in the normalized dermal uptake of DEP and DnBP observed
46
47 416 for exposed fabric in this study, we believe clothing-mediated dermal uptake is an under-
48
49 417 recognized exposure pathway that could be a substantial or even a dominant exposure
50
51 418 route for many chemicals. This is of potential importance in occupational as well as non-
52
53 419 occupational settings.
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

420

421 **Acknowledgements**

422 The authors are grateful to Louise B. Weschler for her assistance with these experiments.

423

424

For Peer Review Only

1
2
3 425
4 426 **References**

- 5
6
7 427
8
9
10 428 1 Rehal B, Maibach H. Percutaneous absorption of vapors in human skin. *Cutan Ocul*
11 429 *Toxicol* 2011; **30**: 87–91.
12
13 430 2 Rauma M, Boman A, Johanson G. Predicting the absorption of chemical vapours. *Adv*
14 431 *Drug Deliv Rev* 2013; **65**: 306–314.
15
16 432 3 Piotrowski J. Further investigations on the evaluation of exposure to nitrobenzene. *Br J*
17 433 *Ind Med* 1967; **24**: 60–65.
18
19
20 434 4 Piotrowski J. Evaluation of exposure to phenol: absorption of phenol vapour in the
21 435 lungs and through the skin and excretion of phenol in urine. *Br J Ind Med* 1971; **28**:
22 436 172–178.
23
24 437 5 Weschler CJ, Nazaroff WW. SVOC exposure indoors: Fresh look at dermal pathways.
25 438 *Indoor Air* 2012; **22**: 356–377.
26
27
28 439 6 Weschler CJ, Nazaroff WW. Dermal uptake of organic vapors commonly found in indoor
29 440 air. *Environ Sci Technol* 2014; **48**: 1230–1237.
30
31 441 7 Gong M, Zhang Y, Weschler CJ. Predicting dermal absorption of gas-phase chemicals:
32 442 Transient model development, evaluation, and application. *Indoor Air* 2014; **24**: 292–
33 443 306.
34
35
36 444 8 Weschler CJ, Beko G, Koch HM, Salthammer T, Schripp T, Toftum J *et al.* Transdermal
37 445 uptake of diethyl- and di(n-butyl) phthalate directly from air: experimental verification.
38 446 *Environ Health Perspect* 2015; doi:10.1289/ehp.1409151.
39
40 447 9 Blum A, Gold MD, Ames BN, Jones FR, Hett EA, Dougherty RC *et al.* Children absorb tris-
41 448 BP flame retardant from sleepwear: urine contains the mutagenic metabolite, 2,3-
42 449 dibromopropanol. *Science* 1978; **201**: 1020–1023.
43
44
45 450 10 Appel KE, Gundert-Remy U, Fischer H, Faulde M, Mross KG, Letzel S *et al.* Risk
46 451 assessment of Bundeswehr (German Federal Armed Forces) permethrin-impregnated
47 452 battle dress uniforms (BDU). *Int J Hyg Environ Health* 2008; **211**: 88–104.
48
49
50 453 11 Rossbach B, Appel KE, Mross KG, Letzel S. Uptake of permethrin from impregnated
51 454 clothing. *Toxicol Lett* 2010; **192**: 50–55.
52
53 455 12 Kegel P, Letzel S, Rossbach B. Biomonitoring in wearers of permethrin impregnated
54 456 battle dress uniforms in Afghanistan and Germany. *Occup Environ Med* 2014; **71**: 112–
55 457 117.
56
57
58
59
60

- 1
2
3 458 13 Schripp T, Salthammer T, Fauck C, Beko" G, Weschler CJ. Latex paint as a delivery
4 459 vehicle for diethylphthalate and di-n-butylphthalate: Predictable boundary layer
5 460 concentrations and emission rates. *Sci Total Environ* 2014; **494**: 299–305.
6
7
8 461 14 Koch HM, Gonzalez-Reche LM, Angerer J. On-line clean-up by multidimensional liquid
9 462 chromatography-electrospray ionization tandem mass spectrometry for high
10 463 throughput quantification of primary and secondary phthalate metabolites in human
11 464 urine. *J Chromatogr B Analyt Technol Biomed Life Sci* 2003; **784**: 169–182.
12
13
14 465 15 Koch HM, Christensen KLY, Harth V, Lorber M, Brüning T. Di-n-butyl phthalate (DnBP)
15 466 and diisobutyl phthalate (DiBP) metabolism in a human volunteer after single oral
16 467 doses. *Arch Toxicol* 2012; **86**: 1829–1839.
17
18
19 468 16 Koch HM, Becker K, Wittassek M, Seiwert M, Angerer J, Kolossa-Gehring M. Di-n-
20 469 butylphthalate and butylbenzylphthalate - Urinary metabolite levels and estimated
21 470 daily intakes: Pilot study for the German Environmental Survey on children. *J Expo Sci*
22 471 *Environ Epidemiol* 2007; **17**: 378–387.
23
24
25 472 17 Koch HM, Lorber M, Christensen KLY, Pälmeke C, Koslitz S, Brüning T. Identifying
26 473 sources of phthalate exposure with human biomonitoring: Results of a 48h fasting
27 474 study with urine collection and personal activity patterns. *Int J Hyg Environ Health*
28 475 2013; **216**: 672–681.
29
30
31 476 18 USEPA. Exposure Factors Handbook: 2011 Edition. US Environmental Protection
32 477 Agency: Washington D.C, 2011.
33
34 478 19 Janjua NR, Frederiksen H, Skakkebaek NE, Wulf HC, Andersson A-M. Urinary excretion
35 479 of phthalates and paraben after repeated whole-body topical application in humans. *Int*
36 480 *J Androl* 2008; **31**: 118–129.
37
38
39 481 20 Moya J, Howard-Reed C, Corsi RL. Volatilization of chemicals from tap water to indoor
40 482 air from contaminated water used for showering. *Environ Sci Technol* 1999; **33**: 2321–
41 483 2327.
42
43 484 21 Moore CA, Wilkinson SC, Blain PG, Dunn M, Aust GA, Williams FM. Use of a human skin
44 485 in vitro model to investigate the influence of 'every-day' clothing and skin surface
45 486 decontamination on the percutaneous penetration of organophosphates. *Toxicol Lett*
46 487 2014; **229**: 257–264.
47
48
49 488 22 Gurunathan S, Robson M, Freeman N, Buckley B, Roy A, Meyer R *et al.* Accumulation of
50 489 chlorpyrifos on residential surfaces and toys accessible to children. *Environ Health*
51 490 *Perspect* 1998; **106**: 9–16.
52
53
54 491 23 Morrison GC, Shakila N, Parker K. Accumulation of gas-phase methamphetamine on
55 492 clothing , toy fabrics and skin oil. *Indoor Air* 2014; **doi: 10.1111/ina.12159**.

- 1
2
3 493 24 Fetter CW. *Contaminant Hydrogeology*. MacMillan Publishing Company: New York,
4 494 1993.
5
6
7 495 25 Mavruz S, Ogulata RT. Investigation of air permeability of single jersey fabrics with
8 496 different relaxation states. *J Text Inst* 2011; **102**: 57–64.
9
10 497 26 Ogulata RT, Mavruz S. Investigation of porosity and air permeability values of plain
11 498 knitted fabrics. *Fibres Text East Eur* 2010; **82**: 71–75.
12
13
14 499 27 Gibson WB, Keller PR, Foltz DJ, Harvey GJ. Diethylene glycol mono butyl ether
15 500 concentrations in room air from application of cleaner formulations to hard surfaces. *J*
16 501 *Expo Anal Environ Epidemiol* 1991; **1**: 369–383.
17
18 502 28 Ghaddar N, Ghali K, Harathani J, Jaroudi E. Ventilation rates of micro-climate air
19 503 annulus of the clothing-skin system under periodic motion. *Int J Heat Mass Transf* 2005;
20 504 **48**: 3151–3166.
21
22
23 505 29 Lyman W, Reehl W, Rosenblatt D. *Handbook of Chemical Property Estimation Methods*.
24 506 American Chemical Society, 1990.
25
26 507 30 Weschler CJ, Salthammer T, Fromme H. Partitioning of phthalates among the gas phase,
27 508 airborne particles and settled dust in indoor environments. *Atmos Environ* 2008; **42**:
28 509 1449–1460.
29
30
31 510 31 Noble RE. Environmental tobacco smoke uptake by clothing fabrics. *Sci Total Environ*
32 511 2000; **262**: 1–3.
33
34 512 32 Chien Y-C, Chang C-P, Liu Z-Z. Volatile organics off-gassed among tobacco-exposed
35 513 clothing fabrics. *J Hazard Mater* 2011; **193**: 139–148.
36
37
38 514 33 Ueta I, Saito Y, Teraoka K, Miura T, Jinno K. Determination of volatile organic
39 515 compounds for a systematic evaluation of third-hand smoking. *Anal Sci* 2010; **26**: 569–
40 516 574.
41
42
43 517 34 Tichenor BA, Sparks LE, Jackson MD, Guo Z, Mason Plunket MACM, Rasor SA. Emissions
44 518 of perchloroethylene from dry cleaned fabrics. *Atmospheric Environ - Part Gen Top*
45 519 1990; **24 A**: 1219–1229.
46
47 520 35 Chao CYH, Tung TCW, Niu JL, Pang SW, Lee RYM. Indoor perchloroethylene
48 521 accumulation from dry cleaned clothing on residential premises. *Build Environ* 1998;
49 522 **34**: 319–328.
50
51
52 523 36 Thomas KW, Pellizzari ED, Perritt RL, Nelson WC. Effect of dry-cleaned clothes on
53 524 tetrachloroethylene levels in indoor air, personal air, and breath for residents of several
54 525 New Jersey homes. *J Expo Anal Environ Epidemiol* 1991; **1**: 475–490.
55
56
57
58
59
60

- 1
2
3 526 37 Sherlach KS, Gorka AP, Dantzler A, Roepe PD. Quantification of perchloroethylene
4 527 residues in dry-cleaned fabrics. *Environ Toxicol Chem* 2011; **30**: 2481–2487.
5
6
7 528 38 Guerrero PA, Corsi RL. Emissions of p-dichlorobenzene and naphthalene from
8 529 consumer products. *J Air Waste Manag Assoc* 2012; **62**: 1075–1084.
9
10 530 39 Schreuder-Gibson H, Truong Q, Walker J, Owens J, Wander J, Jones W. Chemical and
11 531 Biological Protection and Detection in Fabrics for Protective Clothing. *MRS Bull* 2003;
12 532 **28**: 574–578.
13
14
15 533 40 Piadé JJ, D'Andrés S, Sanders EB. Sorption phenomena of nicotine and ethenylpyridine
16 534 vapors on different materials in a test chamber. *Environ Sci Technol* 1999; **33**: 2046–
17 535 2052.
18
19
20 536
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 537
4 538 **Table legend**

5
6
7 539 **Table 1.** Net amount of metabolites excreted during the time period from entering the chamber
8
9 540 until 54 hours later, as well as parent compound uptake calculated from the metabolite levels;
10
11 541 details regarding the calculation of the listed values are presented in Supporting Information.

12
13 542

14
15 543
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

For Peer Review Only

1
2
3 544 **Figure legends.**
4

5
6 545 **Figure 1.** Normalized mass of DEP and DnBP absorbed for fresh and exposed clothes
7
8 546 experiments. Also shown for comparison are results from the 6 bare-skinned participants
9
10 547 (boxplot) reported in Weschler et al.⁸ The line within the box represents the median; the
11
12 548 bottom and top of the box, the 25th and 75th percentiles; the upper and lower whiskers, the
13
14 549 10th and 90th percentiles.
15

16
17
18 550 **Figure 2.** Net amount of MEP (2a) and MnBP (2b) excreted from beginning of exposure
19
20 551 until last urine sample. Results for fresh and exposed clothes are compared against the bare
21
22 552 skin results of the closest aged participant in Weschler et al.⁸
23

24
25 553 **Figure 3.** Normalized dermal uptake of DEP and DnBP versus age. Shown are results from
26
27 554 this research (clothes) and results for six bare skin participants reported by Weschler et
28
29 555 al.⁸
30

31
32 556 **Figure 4.** Normalized metabolite excretion rate for MEP and MnBP. Shown are results from
33
34 557 this research (clothes) and results for six bare-skinned participants reported by Weschler
35
36 558 et al.⁸ The line within the box represents the median; the bottom and top of the box, the
37
38 559 25th and 75th percentiles; the upper and lower whiskers, the 10th and 90th percentiles.
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

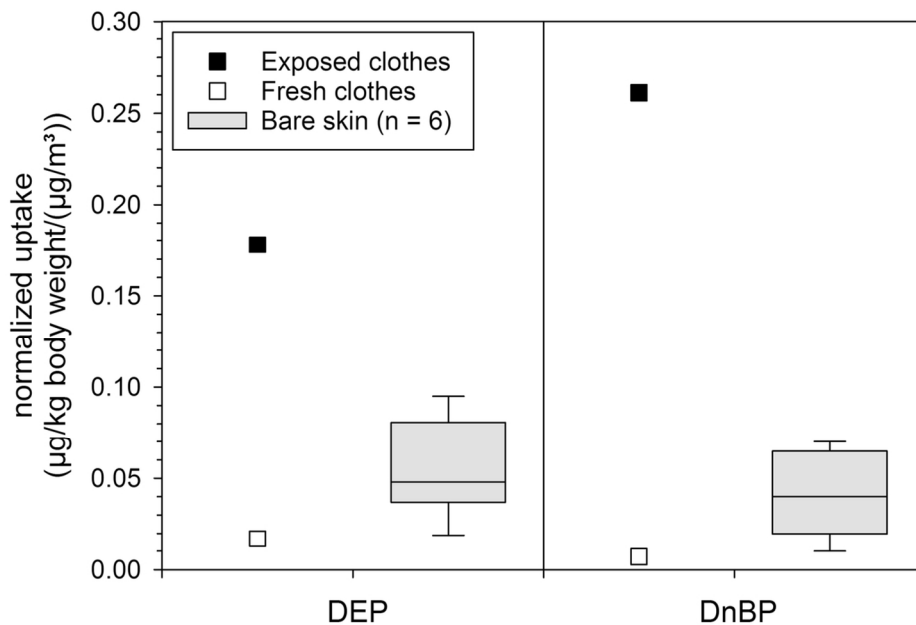


Figure 1. Normalized mass of DEP and DnBP absorbed for fresh and exposed clothes experiments. Also shown for comparison are results from the 6 bare-skinned subjects (boxplot) reported in Weschler et al.⁸ The line within the box represents the median; the bottom and top of the box, the 25th and 75th percentiles; the upper and lower whiskers, the 10th and 90th percentiles.

114x80mm (300 x 300 DPI)

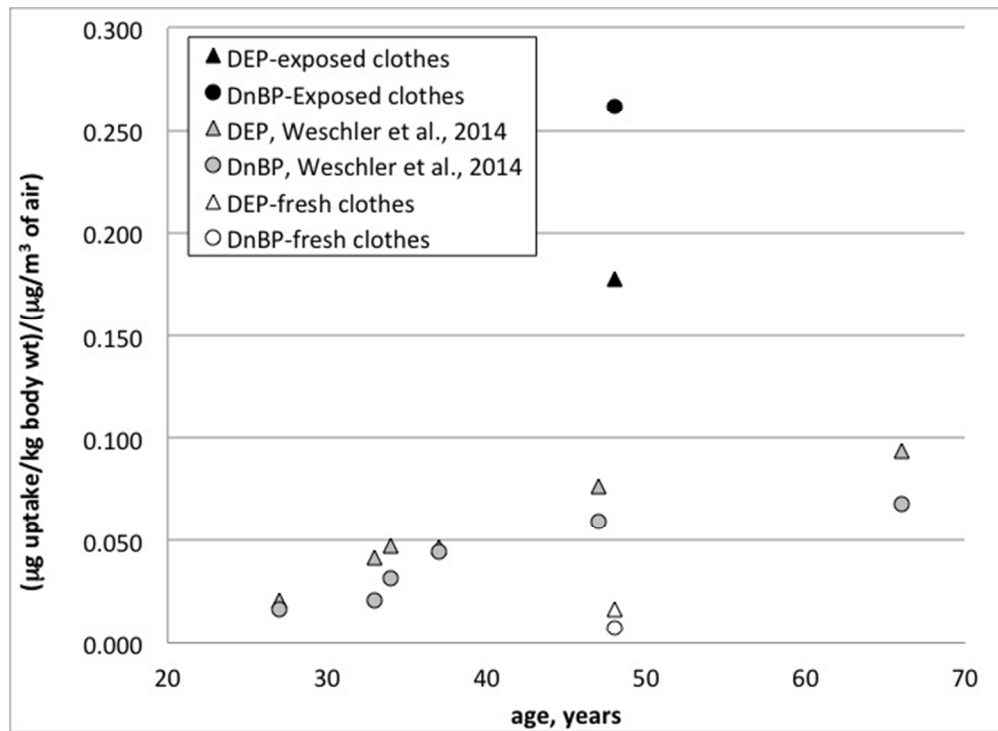


Figure 3. Normalized dermal uptake of DEP and DnBP versus age. Shown are results from this research (clothes) and results for six bare skin subjects reported by Weschler et al.⁸
241x175mm (72 x 72 DPI)

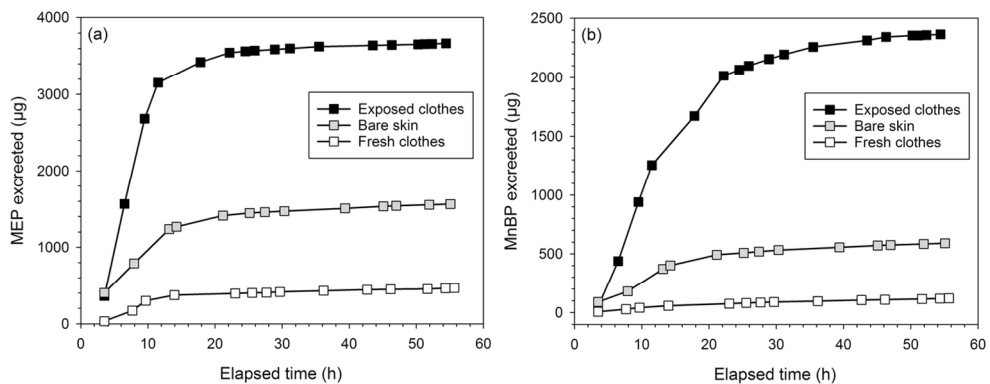
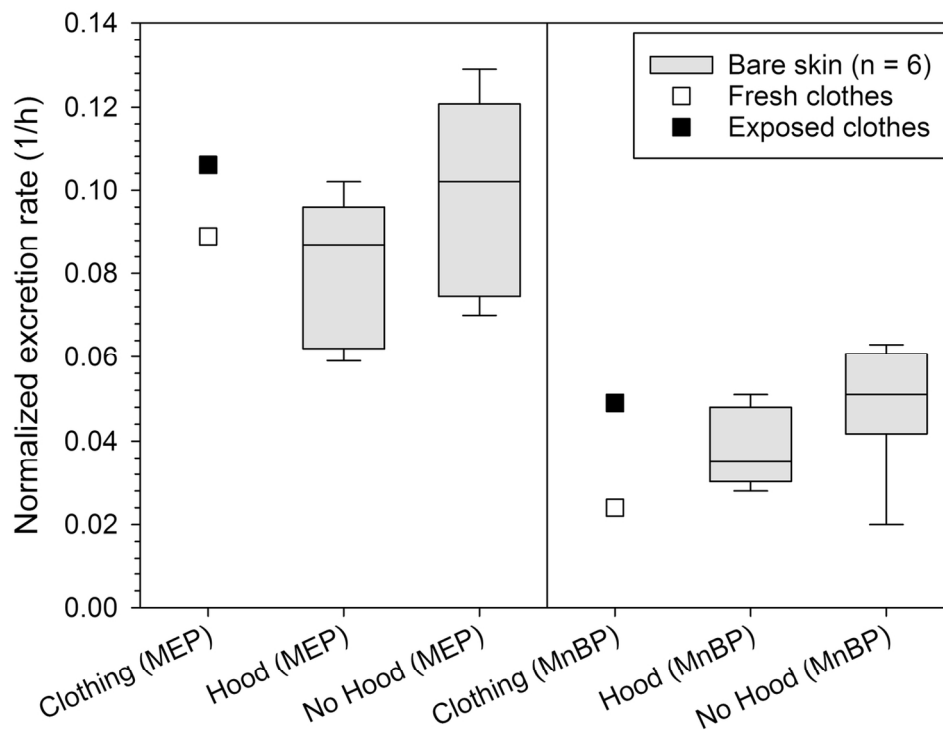


Figure 2. Net amount of MEP (2a) and MnBP (2b) excreted from beginning of exposure until last urine sample. Results for fresh and exposed clothes are compared against the bare skin results of the closest aged subject in Weschler et al.⁸
 121x50mm (300 x 300 DPI)



Normalized metabolite excretion rate for MEP and MnBP. Shown are results from this research (clothes) and results for six bare-skinned subjects reported by Weschler et al.⁸ The line within the box represents the median; the bottom and top of the box, the 25th and 75th percentiles; the upper and lower whiskers, the 10th and 90th percentiles.
129x108mm (300 x 300 DPI)

Only

Table 1. Net amount of metabolites excreted during the time period from entering the chamber until 54 hours later, as well as parent compound uptake calculated from the metabolite levels; details regarding the calculation of the listed values are presented in Supporting Information.

	Metabolites excreted (µg)			Total uptake parent (µg)		Background corrected uptake parent (µg)		Dermal only uptake parent (corrected for concentration in hood) (µg)		Normalized dermal uptake (µg/kg/(µg/m ³))		Average flux based on 6 hour exposure (µg /m ² /h)	
	MEP	MnBP	3OH-MnBP	DEP	DnBP	DEP	DnBP	DEP	DnBP	DEP	DnBP	DEP	DnBP
Fresh clothing	466	121	7.7	634	176	522	98	352	74	0.017	0.007	28	6
Exposed clothing	3666	2367	136	4995	3432	4882	3355	4712	3331	0.178	0.261	381	270

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49

Supplemental Material

Role of clothing in both increasing and decreasing dermal absorption of airborne SVOCs

Glenn Morrison¹, Charles J. Weschler^{2,3}, Gabriel Bekö², Holger Koch⁴, Tunga Salthammer⁵, Tobias Schripp⁵, Jørn Toftum² and Geo Clausen²

¹Civil, Architectural and Environmental Engineering, Missouri University of Science and Technology, 1401 N. Pine St., Rolla, MO 65409, USA

²International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark, DK-2800 Lyngby, Denmark

³Environmental and Occupational Health Sciences Institute, Rutgers University, 170 Frelinghuysen Road, Piscataway, NJ 08854, USA

⁴Institute for Prevention and Occupational Medicine of the German Social Accident Insurance, Institute of the Ruhr-University Bochum (IPA), Bürkle-de-la-Camp-Platz 1, 44789 Bochum, Germany

⁵Fraunhofer WKI, Department of Material Analysis and Indoor Chemistry, Bienroder Weg 54E, 38108 Braunschweig, Germany

Table of Contents for Supplementary Materials	Page
Table S1. Clothing specifications determined from product packaging or labels	3
Figure S1. Male subject shown wearing full set of test clothing and the breathing hood while seated in the test chamber	3
Table S2. Metabolites excreted and parent compound uptake	4

For Peer Review Only

Table S1. Clothing characteristics determined from product packaging or labels

Clothing	Composition	Size	Manufacturer	Description
Undershirt	100% cotton	M/M, 38-40" (97-102 cm)	Gildan	Short sleeve, crew neck, color: white Estimated cloth area = 0.91 m ²
Underwear	100% cotton with elastic band	L/G, 36-38" (91-97 cm)	Hanes	Boxer style briefs, color: grey Estimated cloth area = 0.24 m ²
Shirt	100% cotton	M	Gildan	Long sleeve tee-shirt, crew neck, color: dark green Estimated cloth area = 1.03 m ²
Pants	100% cotton	36" (91 cm) waist 36" (91 cm) inseam	Wrangler	Jeans, slim fit, color: dark blue Estimated cloth area = 1.10 m ²
Socks	85% cotton 12% polyester 1% elastic 1% nylon 1% spandex	12W-15	Starter	Tube socks that rise ~20 cm above ankle, color: white Estimated cloth area (pair) = 0.07 m ²

**Figure S1.** Male subject shown wearing full set of test clothing and the breathing hood while seated in the test chamber.

Table S2. Net amount of metabolites excreted during the time period from entering the chamber until 54 hours later, as well as parent compound uptake calculated from the metabolite levels. This Table is identical to Table 1, but is included here with detailed explanations of calculation methods.

	Metabolites excreted (μg) ¹			Total uptake parent (μg) ²		Background corrected uptake parent (μg) ³		Dermal only uptake parent (corrected for concentration in hood) (μg) ⁴		Normalized dermal uptake ($\mu\text{g}/\text{kg}/(\mu\text{g}/\text{m}^3)$) ⁵		Average flux ($\mu\text{g}/\text{m}^2/\text{h}$) ⁶	
	MEP	MnBP	3OH-MnBP	DEP	DnBP	DEP	DnBP	DEP	DnBP	DEP	DnBP	DEP	DnBP
Fresh clothing	466	121	7.7	634	176	522	98	352	74	0.017	0.007	28	6
Exposed clothing	3666	2367	136	4995	3432	4882	3355	4712	3331	0.178	0.261	381	270

1. The mass of metabolites excreted is determined by multiplying the concentration of each metabolite by the volume of urine collected for each sample and summing over all samples collected during the 54 hour period after the exposure started.

2. Total parent uptake is calculated by converting mass from metabolite to parent and using a metabolic conversion factor.

Compound	Abbreviation	CAS-no.	Molecular weight (g/mol)	Metabolic conversion factor
Diethylphthalate	DEP	84-66-2	222.24	NA
Di-n-butylphthalate	DnBP	84-74-2	278.34	NA
Monoethylphthalate	MEP	2306-33-4	194.18	0.84
Mono-n-butylphthalate	MnBP	131-70-4	222.24	0.84
3OH-mono-n-butylphthalate	3OH-MnBP	57074-43-8	238.24	0.07

$$\text{DEP} = [(\text{MEP} / 194.18) * 222.24] / 0.84$$

$$\text{DnBP} = [(\text{MnBP} / 222.24) * 278.34] + [(3\text{OH-MnBP} / 238.24) * 278.34] / (0.84 + 0.07)$$

3. Background-corrected uptake of the parent compound is determined by subtracting out the background concentration of metabolites, integrating the resulting mass, then applying the conversion described in (2) above. Background is defined as the pre-exposure urine concentration.

4. Dermal uptake of parent compounds is calculated by subtracting from background-corrected uptake the inhaled mass of DEP and DnBP based on concentrations in breathing air of the hood (40.7 and $5.7 \mu\text{g}/\text{m}^3$, respectively). Inhalation rate is assumed to be $0.7 \text{ m}^3/\text{h}$. Therefore, the mass subtracted is 170 and $24 \mu\text{g}$ for DEP and DnBP respectively.

5. Normalized uptake is calculated by dividing the dermal uptake by average exposure air concentration and the subject body mass. Average air concentrations during the fresh clothing experiment were $230 \mu\text{g}/\text{m}^3$ DEP and 113

1
2
3 $\mu\text{g}/\text{m}^3$ DnBP. Average air concentrations during the exposed clothing experiment were 291 $\mu\text{g}/\text{m}^3$ DEP and 140
4 $\mu\text{g}/\text{m}^3$ DnBP.
5
6

7 6. The average flux is estimated from the “Dermal only” corrected parent compound uptake, divided by exposed
8 surface area of the participant and the exposure period (6 hours). Exposed surface area is taken as 2.06 m^2 , estimated
9 by equation 7A-7 of the Exposure Factors Handbook¹⁸ and corrected for the area of the head (6.6% of total).
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

For Peer Review Only