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1 **Influence of the environmental relative humidity on the inflammatory**
2 **response of skin model after exposure to various environmental**
3 **pollutants**

4

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24 **Abstract**

25 The skin is an essential barrier, protecting the body against the environment and its
26 numerous pollutants. Several environmental pollutants are known to affect the skin,
27 inducing premature aging through mechanisms including oxidative stress,
28 inflammation, and impairment of skin functions. Even climate conditions can impact the
29 skin. Therefore, using a Reconstructed Human Epidermis (RHE), we tested the effect of
30 two samples of fine particulate matters (PM_{0.3-2.5} – one metals-rich sample and the other
31 organic compounds-rich), two Volatile Organic Compounds mixtures (VOCs – from a
32 solvent-based paint and a water-based paint) and Tobacco Smoke (TS). All pollutants
33 affected cellular functionality, but to a lesser extent for the water-based paint VOC. This
34 effect was enhanced when RHE were preconditioned for two hours by a semi-dry
35 airflow (45% relative humidity) before pollutants application, compared to
36 preconditioning by a humid airflow (90% relative humidity). In the absence of
37 preconditioning, IL-1 α , IL-6, IL-8, and RANTES were almost systematically induced
38 by pollutants. When RHE were preconditioned by a semi-dry or humid airflow before
39 being subjected to pollutants, the increase of IL-1 α , IL-8, and RANTES falls into two
40 groups. Similarly to RHE not treated with pollutants, RHE treated with VOCs after
41 preconditioning by a semi-dry airflow showed increased IL-1 α , IL-8, and RANTES
42 release. On the contrary, RHE treated with PM or TS after preconditioning by a semi-
43 dry airflow show a lower increase in IL-1 α , IL-8, and RANTES compared to
44 preconditioning by a humid airflow. The effect of real environmental relative humidity
45 conditions of the air, combined with acute exposure to various environmental pollutants,
46 seemed to relate mainly to structural changes of the skin, determining the outcome of

47 the inflammatory response depending on the physicochemical characteristics of
48 pollutants.

49 **Keywords**

50 3D-Skin model

51 Air Liquid exposure

52 Environmental pollutants

53 Environmental humidity

54 Inflammatory response

55

56 **Abbreviations**

57 DMSO: dimethyl sulfoxide, IL: Interleukin, MMPs: matrix metalloproteinases, MTT: 3-

58 (4,5-dimethylthiazol-2-yl)-2,5-diphenylte-trazolium bromide, PM: particulate matter,

59 RH: relative humidity, RHE: Reconstructed Human Epidermis, ROS: reactive oxygen

60 species, SDS: sodium dodecyl sulfate, TS: tobacco smoke, VOCs: volatile organic

61 compounds.

62 **1. Introduction**

63 Air pollution – the degradation of air quality due to harmful gases, chemicals, biological
64 contaminants, and/or particles – is associated with a variety of acute and chronic
65 illnesses leading to increased morbidity and mortality (Hoek et al., 2013; Willers et al.,
66 2013). Like the airway epithelium, the skin is constantly exposed to the environment
67 and its pollutants. It is essential in protecting the body and many factors can affect it.

68 An obvious intrinsic factor that affects the skin is aging. It is visually characterized by
69 the appearance of wrinkles, thinner epidermis, cutaneous dryness, ptosis, loss of
70 elasticity, dark spots, and uneven pigmentation. Central to the process are the increase
71 of oxidative stress, the increase in the activity of matrix metalloproteinases (MMPs)
72 leading to degradation of the extracellular matrix, and the increase in the expression of
73 cytokines and interleukins (Haydont et al., 2019; Parrado et al., 2019). If intrinsic
74 factors can accelerate these processes, extrinsic factors are also important
75 (Makrantonaki et al., 2015). The effect of UVs is well known (Jackson et al., 2001;
76 Flament et al., 2013). Airborne pollutants also exert negative effects on the skin,
77 especially on sensitive skin that can overreact to external aggression (Krutmann et al.,
78 2014).

79 For several years, works agreed that Tobacco Smoke (TS) has a strong impact on the
80 skin. TS is a complex mixture of over 4,000 compounds (CO, HCN, benzene,
81 formaldehyde, nicotine, phenol, polycyclic aromatic hydrocarbons, *etc.*) and only the
82 particulate phase, which represents approximately 5% of the cigarette's total output, is
83 visible as smoke (Hoffmann et al., 1997; Löfrth, 1989; Auer et al., 2017). This complex
84 mixture leads to premature skin aging, wrinkling, poor wound healing, squamous cell
85 carcinoma, and chronic dermatoses (Ortiz and Grando, 2012). *In vivo* studies revealed

86 that TS induces reactive oxygen species (ROS), affects collagen production, and
87 increases the production of tropoelastin as well as MMPs, leading to the degradation of
88 the extracellular matrix (Morita, 2007). We previously corroborate these results, using
89 Reconstructed Human Epidermis (RHE), showing that, if two TS exposures are
90 sufficient to alter the *stratum corneum*, a single one is enough to induce inflammatory
91 cytokines, MMPs, and oxidative stress, as well as down-regulation of essential skin
92 functions (Lecas et al., 2016).

93 Outdoor air pollution is made up of gases (O₃, CO₂, CO, SO₂, and NO_x) and particulate
94 matters (PM). It is considered the world's largest environmental health risk factor due to
95 fine (PM_{2.5}) and ultrafine (PM_{0.1}) particles (WHO, 2018; Loomis et al., 2014). In
96 addition to the respiratory diseases and premature death they induce (Beelen et al.,
97 2014; Raaschou-Nielsen et al., 2013), PM are responsible for premature skin aging,
98 appearance of pigmentation spots, decrease in squalene (a major lipidic component of
99 sebum) and vitamin E, as well as of the increase of lactic acid and melanin, these later
100 indicating oxidative stress (Schikowski and Hüls, 2020). Using RHE we showed that
101 exposure to PM_{0.3-2.5} affects cellular functionality, induces the release of inflammatory
102 cytokines, and leads to oxidative stress (Verdin et al., 2019). PM also have a negative
103 impact on fundamental skin functions: anchorage, cell differentiation, cornification/skin
104 desquamation, and apoptosis.

105 Another source of pollution under scrutiny are Volatile Organic Compounds (VOCs).
106 Defined as organic compounds with a high vapor pressure at normal room temperature
107 (EU, 2010), they represent a numerous, varied, and ubiquitous group of substances.
108 Because of the time people spend inside, VOCs emanating from indoor air pollution are
109 of particular concern. Their sources are numerous including building material,

110 equipment, cleaning products, or even combustion processes such as cooking
111 (Kostiainen, 1995; WHO, 2010). Some of them (toluene, benzene, ethylbenzene, and
112 xylene for instance) are known to have serious adverse effects on human health. So far,
113 the effects of VOCs on the skin is poorly studied. Still, using keratinocytes, Dezest et al.
114 (2017) suggested that VOCs would play a role in premature skin aging. Indeed, they
115 show that VOCs inhibit the proteasome, inducing apoptosis, DNA damage, and protein
116 oxidation.

117 Oxidative stress, inflammation, and metabolic impairments seem to be common
118 mechanisms of skin aging and pollution-induced premature skin aging. Even climate
119 conditions – relative humidity, temperatures – impact skin properties and barrier
120 function and may modify skin reactions (Singh and Maibach, 2013; Cau et al., 2017).
121 Therefore, we evaluated the effect of several pollutants using an RHE system, focusing
122 on inflammation markers. The pollutants tested are two $PM_{0.3-2.5}$ samples with different
123 characteristics, VOCs samples from two different paints and TS. We especially focused
124 on how semi-dry/humid conditions can affect the inflammation response induced by
125 pollutants.

126 **2. Materials and Methods**

127 **2.1. *In vitro* skin model**

128 The *in vitro* skin model used is a reconstructed human epidermis system (RHE) from
129 SkinEthic™ (Lyon, France; Rosdy and Clauss, 1990; Rosdy et al., 1993). It provides a
130 differentiated 3D epidermal tissue from human keratinocytes for which signed informed
131 consent and ethical approval were obtained by the supplier. All experiments were
132 conducted on a single batch (MF22-5).

133 Culture media, growth medium for non-experiment days, and maintenance medium for
134 experiment days were supplemented with 1% of Penicillin-Streptomycin mixture
135 (penicillin: 100 µg/mL; streptomycin: 100UI/mL). Upon reception, RHEs were placed
136 in a 24-well plate with growth medium on the basal side and maintained in an incubator
137 at 37 °C, 5% CO₂, and 95% relative humidity. Experiments were carried out 24h after
138 RHE-acclimation.

139 **2.2. *Fine particulate matters (PM_{0.3-2.5})***

140 Two samples of fine PM, having the same aerodynamic diameter (0.3 to 2.5µm,
141 PM_{0.3-2.5}) and similar granulometric profile, but differing in their sampling origin and
142 their chemical composition were tested: PM from Cotonou (Benin, West Africa) that are
143 rich in metals and inorganic elements (PM_m – metal-rich PM), and PM from
144 Dunkerque (France) that are rich in organic compounds (PM_o – organic-rich PM). The
145 collection and characterization of both PM were already published (Cachon et al., 2014,
146 Dergham et al., 2015). A summary of their composition is presented in Table 1 and
147 detailed analysis in Table S1.

148 Aliquoted and kept at -20°C after collection, PM were thawed and suspended in the
149 maintenance culture medium containing 1% of Penicillin-Streptomycin and 1%

150 fungizone (Thermo Fisher Scientific, Waltham, MA, USA). Twenty-four hours before
151 experiments, PM suspension was sonicated (50W, 10 min, Bath sonicator Branson
152 CPXH, Dutscher, France) and 30 μL were deposited onto the apical side of RHEs.
153 Three concentrations – 3, 15, and 30 $\mu\text{g}/\text{cm}^2$ – as previously described (Verdin et al.,
154 2019) were tested. Medium without PM was used as a negative control.

155 **2.3. Volatile organic compounds (VOCs)**

156 VOC atmospheres were generated from two different paints, which containers have
157 never been opened). VOCwb (water-based) are from an aqueous paint (Brillant Intérieur
158 Acrylique, Auchan, France) bought in 2014, after the French regulation governing
159 construction and decoration labeling (decrees 19/04/2011 and 20/04/2012 that set the
160 upper limit of VOCs to 20 g/L; European Union, 2010 and the French decree 2011-321
161 (March 23, 2011) related to the mandatory labeling of VOCs emission of building and
162 decoration products. VOCsb (solvent-based) are from an alkyd paint (Brillant, Orion
163 line, Guittet, France) manufactured before 2007, and thus before the above-mentioned
164 decrees.

165 The protocol applied to generate VOCs atmospheres was inspired by the emission
166 standard test (ISO 16000-9, ISO, 2006a) and the paints were prepared according to
167 ISO 16000-11 (ISO, 2006b). Briefly, paint was spread onto a 150 cm^2 glass plate that
168 was then placed in an 11 L sealed generation chamber under a steady airflow (20-25°C,
169 $79 \pm 8\%$ humidity and a rate of 0.5 L/h (Ricquebourg et al., 2015). The VOCs
170 atmosphere was stabilized for 3 days before exposure. Samplings of VOCs from paint
171 were chemically controlled by vacuum vial SPME sampling (Desauziers and Auguin,
172 2012) followed by GC/MS/FID analysis. The concentrations of VOCwb and VOCsb

173 were determined as toluene equivalent from the FID signal (Badji et al., 2018) and are
174 summarized in Table 2 and detailed in Table S2.

175 On the day of exposure, the generation chamber was connected to the Vitrocell®
176 dynamic exposure system (Vitrocell System® GmbH, Waldkirch, Germany). This
177 system contains six exposure chambers, each one with an insert with the RHE tissue
178 and a trumpet. For one hour, a 2mL/min airflow was created to deliver the VOC
179 atmosphere through the trumpet, onto the apical side of the RHE that was maintained at
180 37°C thanks to a water bath (Persoz et al., 2010). An atmosphere without VOCs,
181 delivered with the same dynamic system, was used as a negative control.

182 **2.4. Tobacco smoke (TS)**

183 TS that is a complex mixture containing polycyclic aromatic hydrocarbons, volatile
184 organic compounds, and PM present in air pollution was used as positive environmental
185 pollution control. For this purpose, mainstream tobacco smoke (TS) was generated by
186 the combustion of a French brand cigarette composed of 87% tobacco, 6.5% flavors
187 agents, and 6.5% cigarette paper. It produces 7 mg of tar, 0.6 mg of nicotine, 9 mg of
188 carbon monoxide and comprises two parts, gas and particulate matter.

189 Using a static system adapted from the Vitrocell Cloud™ chamber (Vitrocell System®
190 GmbH, Germany), fresh TS was delivered to the apical face of RHE at a rate of 25 mL
191 per puff with a total of 10 puffs (Lecas et al., 2016; Bardet et al. 2016). The dose
192 delivered corresponds to one cigarette, with an average of 200 µg/cm² of particulate
193 matters. Similarly to RHEs treated with VOCs, the air atmosphere used to generate TS
194 was used as a negative control.

195 **2.5. Exposure of RHEs to pollutants**

196 To compare the effect of the sole pollutants, RHEs were exposed to pollutants as
197 described above, then incubated for 24h in classical culture conditions (incubator at
198 37°C, with 5% CO₂, and 90% relative humidity). RHEs not subjected to pollutant were
199 used as negative controls (Fig. 1A, 1C).

200 For all experimental series, at the end of the incubation period, culture media were
201 collected to assess the immune response by quantifying cytokines/chemokines release,
202 and RHEs were harvested to perform MTT assay.

203 ***2.6. Preconditioning of RHE to semi-dry/humid airflow followed by exposure to*** 204 ***pollutants***

205 To assess the role of humidity on the impact of pollutants, RHE were preconditioned by
206 a semi-dry or humid airflow for 2h before being incubated with pollutants. RHE
207 maintained at 37°C thanks to a water bath, were subjected to different airflows. The
208 airflow was delivered using the Vitrocell[®] Humidification Station (Vitrocell Systems[®]
209 GmbH, Waldkirch, Germany) that was supplying semi-dry air (24°C, 5% CO₂ and 45%
210 relative humidity (RH) similarly to European conditions like in Dunkerque city) or
211 humid air (24°C, 5% CO₂ and 90% RH representative of conditions in South America,
212 Asia or Africa, like in Cotonou city). Then, RHEs were exposed to pollutants as
213 described above, and further incubated for 24 h in classical culture conditions (37°C,
214 with 5% CO₂, and 95% RH) before performing MTT assays on RHE and quantifying
215 cytokines/chemokines released in the culture media.

216 The protocol of exposure is described in Fig. 1B. Various controls were considered and
217 are summarized in Fig. 1C. Negative controls: RHEs preconditioned by the humid or
218 semi-dry airflow but not exposed to pollutants, and RH controls: RHEs exposed to the

219 pollutants but not to preconditioning by the humid/semi-dry airflow (kept in the
220 incubator at 37°C with 90% RH).

221 **2.7. Cellular functionality: MTT assay**

222 Cellular functionality was assayed on the basal side of RHE relying on the ability of the
223 mitochondrial succinate dehydrogenase to convert MTT (3-(4,5-dimethylthiazol-2-yl)-
224 2,5-diphenyltetrazolium bromide) into a formazan product that has a maximum
225 photometric absorbance at 490 nm (Persoz et al., 2010). Briefly, 24h after exposure, the
226 culture medium was removed, 500 µL of MTT was added to the bottom of the well
227 containing the RHE. After two hours of incubation (37°C, with 5% CO₂, and 95%
228 relative humidity), DMSO (500µL) was added to the bottom of the well, reagents were
229 homogenized by shaking and transferred to 96-well plates. Absorbance was read using a
230 microtiter plate reader (Multiskan[®] EX, Thermo Scientific, Waltham, MA, USA).

231 **2.8. Mapping of cytokine production: Q-Plex[™] analysis**

232 Q-Plex[™] quantitative ELISA-based chemiluminescent assay (Quansys, Logan, UT,
233 USA) were performed according to the manufacturer's instructions, using the profiling
234 service of Tebu-bio (Le Perray-en-Yvelines, France). Nine cytokines (Q-Plex Human
235 Cytokine-Inflammation #110433HU – IL-1α, IL-1β, IL-2, IL-4, IL-6, IL-8, IL-10,
236 IFNγ and TNFα) and eight chemokines (Q-Plex Human Chemokine Inflammation
237 #110451HU – Eotaxin, GROα, I-309, IP-10, MCP-1, MCP-2, RANTES and TARC)
238 were measured. The analysis was performed by quantifying the intensity of the
239 chemiluminescent signals on the Tebu-bio technological platform using both Q-View[™]
240 and Quansys Software. Sensitivity ranges between 1 pg/mL and 30 pg/mL depending
241 on the considered analyte.

242 **2.9. Specific cytokine/chemokine production: ELISA analysis**

243 Two cytokines and one chemokine were assessed using Human DuoSet ELISA (R&D
244 Systems, Minneapolis, MN, USA) interleukin 1 α (IL-1 α /IL-1F1, #DY200), interleukin
245 8 (IL-8/CxCL8, #DY208) and RANTES (CCL5/RANTES, #DY278). Absorbance was
246 determined using an ELISA-reader (Multiskan[®] EX, Thermo Scientific, Waltham, MA,
247 USA) at 450 nm and 540 nm to correct the optical imperfections in the plate.
248 Calibration curves were calculated using Ascent Software[®] (Thermo Fisher Scientific,
249 Waltham, MA, USA). Concentrations are expressed in pg/mL and the lower limits of
250 quantification are 31.26, 7.81, 156 pg/mL for IL-8, IL-1 α , and RANTES, respectively.

251 ***2.10. Statistical analysis***

252 All results are reported as mean \pm standard deviation. Except for Q-Plex[™] analysis that
253 was performed only once with duplicated quantification, all other experiments were
254 performed at least in two independent experiments, each with duplicated quantification.
255 The exact number of independent experiments (n) is indicated in the legend of the
256 figures. After verifying the Normal distribution of results using the Shapiro-Wilk test
257 ($p < 0.05$), statistical differences were analyzed using one-way ANOVA followed by
258 Tukey HSD (Honestly Significant Difference) test. $p < 0.05$ was considered significant.

259 **3. Results**

260 **3.1. RHE functionality upon exposure to pollutants**

261 RHEs were exposed to various environmental pollutants: two PM_{0.3-2.5} samples – PMm,
262 rich in metals and inorganic elements, and PMo, rich in organic compounds – two VOC
263 mixtures – VOCwb, emanating from a water-based paint, and VOCsb, from a solvent-
264 based paint – and TS.

265 Results of the MTT assay (Fig. 2) reveals that the pollutant which most affects RHE is
266 TS, inducing a significant -43.9% (p<0.0001) decrease in cell functionality compared to
267 the negative control. Moreover, both PM were found to alter the functionality of RHEs.
268 The effect is dose-dependent and statistically significant from the lowest exposure doses
269 to 3 µg/cm² of PMm (-10.5%, p=0.0155) or 15 µg/cm² of PMo (-15.4%, p<0.0001). The
270 negative effect is higher when RHEs are exposed to PMm than to PMo,
271 reaching -39.4% (p<0.0001) for exposure to 30 µg/cm² of PMm, while the decrease
272 induced by PMo is of -26.7% (p<0.0001). Among the two VOCs tested, only VOCsb
273 affects RHEs, leading to -8.7% (p=0.0213) in cell functionality, the -4.4% decrease
274 induced by VOCwb being not significant (p=0.4543).

275 **3.2. RHE functionality upon preconditioning in a semi-dry or humid airflow** 276 ***followed by exposure to pollutants***

277 To evaluate the impact of airflow with different relative humidity on the effect of
278 pollutants, we preconditioned RHEs by submitting them to a semi-dry (45% relative
279 humidity – RH) or a humid (90% RH) airflow for 2 hours prior exposure to pollutants.
280 Controls included negative controls, preconditioned by the semi-dry or humid airflow
281 but not subjected to pollutants, and RH controls, incubated with pollutants but not to

282 preconditioning by the humid/semi-dry airflow (kept in the incubator at 37°C with 90%
283 RH).

284 Results (Fig. 3) showed that, for the negative control, preconditioning by the humid
285 airflow does not affect RHE compared to the RH control. This lack of effect of
286 preconditioning by the humid airflow is also observed when comparing RHE incubated
287 with pollutants with their respective RH controls. Only preconditioning by the semi-dry
288 airflow affects the results of the MTT test for both, the negative control and the RHE
289 treated with the various pollutants. The decrease is always significant when results are
290 compared to that of RHE preconditioned by the humid airflow and almost always when
291 compared to the respective RH controls (the exception being PM_m). Still, within series,
292 the decrease in cellular functionality induced by the semi-dry preconditioning compared
293 to preconditioning by the humid airflow remains generally mild (negative control: -
294 12.9%, p=0.0443; PM_m: -16.7%, p=0.0242; PM_o: -19.8%, p=0.0014; VOC_{wb}: -23.9%,
295 p<0.0001; VOC_{sb}: -26.6%, p<0.0001), except for TS for which it reaches -34.1%
296 (p=0.0007).

297 **3.3. Inflammatory response upon exposure to pollutants**

298 We have then investigated the inflammatory response induced by pollutants by
299 monitoring the production of nine cytokines (IL-1 α , IL-1 β , IL-2, IL-4, IL-6, IL-8,
300 IL-10, IFN α , TNF α) and eight chemokines (Eotaxin, GRO α , I-309, IP-10, MCP-1,
301 MCP-2, RANTES, TARC). The results are presented in Fig. 4.

302 IL-1 α , IL-6, IL-8, and RANTES are the only cytokines/chemokines almost
303 systematically and significantly induced by a factor of 1.3 to 2.7 by pollutants: PM at
304 15 $\mu\text{g}/\text{cm}^2$ and over, VOCs and TS. Even if VOC_{wb} does not significantly induce
305 IL-1 α /IL-6 and TS does not significantly induce IL-8, the probabilities are at the limit of

306 significance for IL-1 α and VOCwb (p=0.0535), as well as for IL-8 and TS (p=0.0903).
307 For both PM a dose-dependent effect is clearly observed for IL-1 α , IL-6, IL-8, and
308 RANTES. Besides, the induction of the three cytokines/chemokines seems to be higher
309 for PMm (x2.2 folds for IL-1 α , x2.7 folds for IL-6, x2.7 folds for IL-8 and 2.1 folds for
310 RANTES with 30 $\mu\text{g}/\text{cm}^2$) than for PMo (x2.1 folds for IL-1 α , x1.9 folds for IL-6, x2.1
311 folds for IL-8 and 1.8 folds for RANTES with 30 $\mu\text{g}/\text{cm}^2$).
312 In these experimental series, none of the pollutants induced IL-1 β , IL-4, Eotaxin, I-309,
313 MCP-2 or TARC, and the induction of IL-2, IL-10, IFN α , TNF α , GRO α , IP-10, MCP-1
314 depends on the pollutant. Still, overall PMm is the pollutant inducing the most
315 cytokines and chemokines (10 among the 17 tested) while VOCwb is the one inducing
316 the least (5), VOCsb, and TS being intermediate.

317 ***3.4. Inflammatory response upon preconditioning in a semi-dry or humid airflow***
318 ***followed by exposure to pollutants***

319 To analyze the effect of airflows with different relative humidity on the inflammatory
320 response induced by pollutants, we preconditioned RHEs for two hours using a semi-
321 dry or humid airflow before subjecting them to pollutants. For this analysis, we focused
322 on IL-1 α , IL-8, and RANTES that were induced by most pollutants tested. Similarly to
323 the study of the cellular functionality of both, semi-dry/humid airflow and pollutants,
324 the controls encompassed negative controls, subjected to preconditioning by the
325 different airflows but not to pollutants, and RH controls, subjected to pollutants but not
326 to preconditioning by the airflows. The results are presented in Fig. 5.

327 In the negative controls, comparison of the amount of cytokines/chemokine released by
328 the RH controls and by RHEs preconditioned by the 90% RH airflow shows that
329 preconditioning by the humid airflow significantly increases the release of IL-1 α and

330 IL-8 by a factor of 1.9, while, for RANTES, the increase is not significant. The increase
331 in IL-1 α and IL-8 is also observed when comparing RH controls treated with pollutants
332 and RHEs which underwent both, preconditioning by the humid airflow and incubation
333 with pollutants, but, in that case, the increase is also significant for RANTES. In
334 addition, the fold change compared to RHE treated with pollutants but not
335 preconditioned by the humid airflow is much higher, reaching over 10 folds for IL-8
336 induction by any of the PM and 3 to 5 folds for RANTES inductions by whatever
337 VOCs.

338 For all negative controls, preconditioning in the semi-dry airflow significantly increases
339 the release of IL-1 α , IL-8 and RANTES compared to the RH controls. Except for IL-1 α ,
340 this increase is significantly higher than that obtained upon preconditioning by the
341 humid airflow. When RHEs are treated with both, preconditioning by the semi-dry
342 airflow and either PM, the release of IL-1 α , IL-8 and RANTES is higher than in the RH
343 controls, but overall significantly lower than when RHEs are preconditioned by the
344 humid airflow. For TS, combination with preconditioning by the semi-dry airflow acts
345 similarly to PM on IL-1 α , IL-8, and RANTES. Contrary to PM and TS, preconditioning
346 by the semi-dry airflow and either VOC, VOC_{wb}, or VOC_{sb}, leads to an increase in
347 IL-1 α , IL-8, and RANTES compared to preconditioning by the humid airflow.

348 **4. Discussion**

349 In recent years, several studies were devoted to the biological effect of air pollutants.
350 Many focused on small particulate matters ($PM_{<2.5}$) due to their role in pulmonary
351 morbidity and mortality. But PM are not the only source of air pollution and, with the
352 increasing time spent inside, VOCs are also important to consider. Besides, the majority
353 of the studies focuses on the pulmonary epithelium. Little is known about the fate of the
354 skin despite the fact it is the largest human organ and it is also constantly exposed to the
355 environment. Therefore, we wanted to better understand the impact of air pollutants on
356 the skin and, especially, to investigate how an environmental factor such as humidity
357 affects the response to pollutants knowing that changes in relative humidity are
358 sufficient to impact the skin (Singh and Maibach, 2013; Cau et al., 2017).

359 Among the pollutants we tested, TS was primarily used as a positive control. This
360 pollutant is a complex mixture containing over 4,000 gaseous and particulate
361 compounds, including VOCs and PM. Its effect on premature skin aging is already well
362 documented and we previously showed, using the very same RHE system, that it
363 induces morphological alterations, oxidative stress, leading to the production of
364 inflammatory cytokines (Lecas et al., 2016). Therefore, our primary interest was the
365 response induced by two types of pollutants, fine particles ($PM_{0.3-2.5}$) and VOCs, with
366 two different samples for each. Both PM samples present similar granulometric profiles,
367 but show very different chemical compositions, therefore enabling us to evaluate the
368 impact of chemicals adsorbed to the particles. PMm are originating from a highly
369 polluted urban region of Sub-Saharan Africa (Cotonou, Benin). They are characterized
370 by their extreme richness in metallic elements as the region where they were collected is
371 surrounded by soils with high concentrations of iron oxide, aluminum oxide, and heavy

372 metals (Cachon et al., 2014). On the contrary, PM₁₀ are from a region of France
373 (Dunkerque) with intense industrial activities and heavy vehicle traffic, which their
374 richness in organic compounds reflects (Dergham et al., 2015). The last two pollutants
375 we tested are VOCs. Much less studied, we focused on VOCs from a solvent-based
376 paint that was manufactured before the French regulation limiting VOCs in construction
377 and decoration products and that liberates large amounts of various VOCs. The second
378 source of VOCs is a recent water-based paint manufactured after the French regulation
379 and showing reduced VOCs emissions.

380 All these pollutants are real environmental pollutants. In addition, the exposure system
381 we set up is realistic in the sense that the pollutants are delivered to the apical side of
382 RHEs, therefore mimicking a real-life situation. Still, it is inhomogeneous in its
383 exposition due to the physical nature of the different pollutants tested. As a matter of
384 fact, PM are applied topically and remain on RHE for 24 hours before analysis, making
385 it a static system. On the other hand, VOCs are delivered dynamically, via a one-hour
386 airflow followed by a 24-hours incubation before analysis. The system we used for TS
387 is intermediate. Fresh TS is generated in a chamber where its compounds are allowed to
388 interact with, and sediment onto RHEs. Therefore, it is more of a static system that
389 favors the action of the PM constituents that will stay on RHEs, rather than that of its
390 gaseous phase for which the contact is time-limited. Another source of inhomogeneity is
391 the dose of pollutants tested. If the doses of PM and TS we tested are much higher than
392 normal exposures, as frequently in *in vitro* studies, those of VOCs are, on the contrary,
393 very low: 6.1 µg/liter for VOC_{wb} and 183.5 µg/liter for VOC_{sb}, therefore 0.73 µg and
394 22.0 µg respectively during the one-hour exposure. These low doses are due to the fact
395 that we followed the ISO standards to generate the VOCs samples.

396 Not only does our experimental setup show heterogeneity in the testing of pollutants,
397 but the pollutants we tested are very different and interact differently with the skin. PM
398 are a complex mixture of insoluble particles – the physical part – and soluble
399 components absorbed to their surface – the chemical part. If PM can induce their effects
400 through the release of soluble components that can enter the stratum corneum, the
401 tiniest PM can enter the skin. Indeed, Jin et al. (2018) showed that PM can enter the
402 skin by accumulating in hair follicles and sweat glands. In RHE, they were found to
403 enter the upper layers in less than 24 hours (Magnani et al., 2015), which is not
404 surprising regarding the fact that PM break the skin barrier by down-regulating
405 filaggrin, thereby disrupting the tight skin junctions (Pan et al., 2015; Lee et al., 2016).
406 RHEs are deprived of hair follicles and sweat glands, but we incubated them with PM
407 for 24 hours. Therefore, it seems likely that the toxicological endpoint we observe is
408 due to both, the prolonged contact and/or diffusion of soluble components through the
409 surface of the stratum corneum, as well as to the direct release of compounds absorbed
410 to their surface within the upper layers of RHE. On their side, VOCs must have directly
411 diffused into the upper layers of RHE. Indeed, the toxicity of hexane and toluene, two
412 VOCs, relates to their lipophilicity and their accumulation in the lipid bilayer of cellular
413 membranes (Dreiem et al., 2003; Pariselli et al., 2009). Besides, VOCs are also known
414 to affect the skin due to the ability of UV and NO_x to transform them into
415 photochemical oxidants, which seems unlikely to have played a major role considering
416 our experimental setup.

417 Whatever the entry route of the pollutants, inhibition of the succinate dehydrogenase
418 revealed by the MTT assay shows that PM, TS, and VOCsb affect RHEs. For the two
419 PM, the alteration is dose-dependent, and the effect is stronger when RHE are treated

420 with PMm than with PMo. This may result from the high level of transition metals and
421 other metals adsorbed on PMm (*e.g.* Al, Cu, Fe, Mn, Zn, Pb, *etc.*) that are powerful
422 ROS inducers. Using the same exposure system, we previously showed that PMm are
423 powerful inducers of oxidative stress (Verdin et al., 2019). The fact that polycyclic
424 aromatic hydrocarbons adsorbed to PM bind the aryl hydrocarbon receptor (AhR) to
425 induce a signaling pathway leading to ROS formation and proinflammatory gene
426 expression is now well established (Esser et al., 2018; Parrado et al., 2019). Oxidative
427 stress was also demonstrated for PMo using BEAS-2B bronchial epithelial cells
428 (Dergham et al., 2015). Evidence of oxidative stress was also found for keratinocytes
429 exposed to different VOCs (Dezest et al., 2017). Oxidative stress and inflammation are
430 tightly linked and, if ROS are not controlled, they lead to inflammatory cell and/or
431 tissue injury (Lonkar and Dedon, 2010). In our case, all pollutants tested induce
432 RANTES and almost all of them IL-1 α as well as IL-8. Similarly to the cellular
433 functionality, the effect is more pronounced for PMm, which also induces more
434 cytokines and chemokines, than PMo. The induction of cytokines and chemokines
435 production is also observed with the two VOCs and TS even if the range of cytokines
436 and chemokines induced is more limited, especially for VOCwb.

437 When testing the influence of preconditioning by a humid *versus* a semi-dry airflow,
438 results show that the semi-dry airflow impacts cellular functionality, whatever pollutant
439 tested. Negative controls also revealed increased levels of IL-8 and RANTES upon
440 preconditioning by the semi-dry airflow. If airflows differ between them by their
441 relative humidity, they also differ from the negative control by the temperature (24°C).
442 Still, RHEs are maintained at 37°C and it is only their apical side that is subjected to
443 this lower temperature. Hence, it sounds reasonable to assume that most of the effect we

444 observed is due to the differences in relative humidity, and that the increased levels of
445 IL-8 and RANTES could be the first consequence of the initial increase in
446 Transepidermal Water Loss (TEWL) followed by inflammatory cytokine stimulation as
447 described in studies performed in dry conditions (Singh and Maibach, 2013). Still,
448 results show that the short preconditioning period in semi-dry or humid air is sufficient
449 to affect the reaction of RHE towards pollutants. Contrary to cellular functionality, the
450 different preconditioning is also sufficient to reveal different effects depending on the
451 type of pollutants. For both PM and TS, preconditioning by the semi-dry airflow tends
452 to decrease the levels of IL-1 α , IL-8, and RANTES compared to preconditioning by the
453 humid airflow. The situation is just the opposite for the induction of IL-1 α , IL-8, and
454 RANTES by the two VOCs. Strikingly, both VOCs induce an almost identical response
455 despite their very different qualitative and quantitative compositions. This response is
456 similar to that of the negative control and suggests that, under the conditions used (low
457 doses and short exposure), the effect of preconditioning by the semi-dry airflow primes
458 over the response to VOCs. Taken together, these results suggest that the response of
459 the skin to RH is the main driver of the toxicological endpoint and that its outcome
460 depends mainly on the physical nature of the pollutant.

461 Several works studied the effect of dry conditions on the skin (reviewed in Engebretsen
462 et al., 2016; Goad and Gawkrödger, 2016). They show that human skin placed in dry
463 conditions presents an increased stratum corneum thickness, an increased TEWL, a
464 reduced elasticity, and an increased susceptibility to mechanical stress. In hairless mice,
465 dry condition (3 days at 10% RH) induces reduced desmosomal degradation that was
466 attributed to the reduced water content of the stratum corneum, leading to impaired
467 desquamation and a scaly surface (Sato et al., 1998). Furthermore, the amount of IL-1 α

468 was found higher in mice kept under dry conditions (Ashida et al., 2001). RHE
469 produced in semi-dry conditions (30-50% RH) also show increased TEWL, a thicker
470 stratum corneum, and an increased level of epidermal protein deimination. These
471 alterations lead to the breakdown of filaggrin, a filament-associated protein that binds to
472 keratin fibers in epithelial cells (Cau et al., 2017). If all these works pinpoint at a barrier
473 deficit when the skin is subjected to dry conditions, one should be cautious in
474 extrapolating them to our study. Most of the works mentioned above were performed
475 comparing much longer incubation times in different RH conditions than the two hours
476 preconditioning time we used. In our case, preconditioning by the semi-dry airflow
477 might have only led to the very first step of the above-mentioned changes: the increased
478 water loss, the beginning of the dehydration of the upper layers of the stratum corneum
479 and, as we show it, the release of cytokines/chemokines. Therefore, for VOCs the effect
480 we observe would be driven by our dynamic experimental setup and would only reflect
481 the effect of the two hours preconditioning in semi-dry conditions.

482 The fate of PM would be different but can also be explained by the mechanical
483 characteristics of the skin under the different RH conditions. In that respect, the static
484 experimental design we used for TS reflects the particulate nature of TS rather than that
485 of its gaseous part since it induces a similar response than PM. Two mutually none
486 exclusive aspects could explain the lower cytokine/chemokine induction observed upon
487 preconditioning by the semi-dry airflow compared to the humid airflow. The first one is
488 that, as mentioned above, the semi-dry airflow rapidly lead to dehydration of the upper
489 layer of the stratum corneum and a scaly surface. These could have limited the contacts
490 between PM and RHE and/or limited the diffusion of the chemical components
491 absorbed to the surface of PM. On the other hand, preconditioning under humid

492 conditions might have favored these contacts. Using transmission and cryo-scanning
493 electron microscopy, Warner et al. (2013) show that a four-hours treatment in an
494 atmosphere saturated with water leads to a three-fold increase in the thickness of the
495 stratum corneum with large pools of water accumulating in intercellular spaces where
496 the lipid structures are disrupted. This study was performed *in vivo*, on the volar
497 forearm of volunteers. With the weaker stratum corneum of RHE, we can assume that
498 such an effect can occur when they are maintained under 90% RH. Not only would it
499 explain better contact between PM and the upper cell layers, but the rupture of the
500 stratum corneum barrier and the large pool of water might lead to an increased entry of
501 PM. It would also explain a better diffusion of the metallic elements absorbed to the
502 surface of PMm and, therefore, the stronger release of IL-1 α , IL-8, and RANTES.

503 It is important to note that our conclusions are quite limited by the fact that the
504 experiments were performed on a single batch of RHE which are known to show some
505 inter-batch variability. A last limitation is due to the short period during which RHE can
506 be used. This restricts the use of our system to the test of short exposure periods and
507 precludes us from testing chronic like exposure. Still, the use of a 3D-skin model – a
508 reconstructed human epidermis – enabled us to mimic the effects of close contact
509 between pollutants and the skin. The experimental system we set up also allowed us to
510 test realistic environmental pollutants. Not only are they realistic in their generation
511 and, by extension, in their physicochemical composition but, also, in the way we
512 delivered them to RHE, which reflects the real human dermal exposure route: an air-
513 liquid exposure resulting in the topical application of pollutants. Finally, the use of the
514 innovative humidification station has proven to be suitable, and the conditions we tested

515 are representative of real environmental conditions, since the 2 hours preconditioning is
516 sufficient to induce different reactions towards various environmental pollutants.

517 **Conclusion**

518 In the course of this study, we tested various pollutants with different chemical
519 compositions, applying them to the apical side of RHE and being particularly interested
520 in the effect relative humidity has on the reaction to pollutants. The negative effect of
521 pollutants on the cellular functionality is aggravated when RHE are preconditioned for
522 two hours by a semi-dry airflow. Investigating several cytokines and chemokines, we
523 showed that IL-1 α , IL-6, IL-8, and RANTES are the cytokines/chemokines almost
524 systematically induced by most pollutants. When RHE are preconditioned by a semi-
525 dry/humid airflow before being subjected to pollutants, the release of IL-1 α , IL-8, and
526 RANTES falls into two groups. For VOCs, preconditioning by a semi-dry airflow
527 exacerbates IL-1 α , IL-8, and RANTES release, similar to what happens in the absence
528 of pollutants, indicating a response driven by RH rather than by VOCs. On the other
529 hand, for PM and TS, preconditioning by a semi-dry airflow leads to a decrease in the
530 release of IL-1 α , IL-8, and RANTES. Our interpretation is that the effect of RH on the
531 skin structure primes over the chemical composition of the pollutants. It is the changes
532 induced by the different humidity conditions – and our experimental design – that
533 determine the outcome of the toxicological endpoint of a pollutant depending on its
534 physical nature.

535 **Declaration of interest**

536 The authors declare no conflict of interest.

537

538 **CRedit authorship contribution statement**

539 **Emeline Seurat:** Conceptualization, Methodology, Formal analysis, Writing-original
540 draft. **Anthony Verdin:** Conceptualization, Methodology, Formal analysis,
541 Investigation, Proof-reading. **Fabrice Cazier:** Conceptualization, Methodology, Formal
542 analysis, Investigation, Proof-reading. **Dominique Courcot:** Supervision, Proof-
543 reading. **Richard Fitoussi:** Funding acquisition, Supervision, Proof-reading. **Katell**
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546 **Nathalie Seta:** Supervision, Proof-reading. **Sophie Achard:** Conceptualization,
547 Methodology, Formal analysis, Investigation, Writing-original draft, Visualization,
548 Ressources, Data curation, Funding Acquisition, Supervision.

549

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741 **Tables**

742

743 **Table 1**

744 Summary of the main metallic and organic components of PMm (Cotonou, Benin -
745 Cachon et al., 2014) and PMo (Dunkerque, France - Dergham et al., 2015).

| Chemicals | PMm (ng/m ³) | PMo (ng/m ³) |
|--|------------------------------------|------------------------------------|
| Metallic elements (Al, Ba, Cr, Cu, Fe, Mn, Ni, Pb, Ti, V, Zn) | 8,644 | 620 |
| Water-soluble ions (Ca ²⁺ , Cl ⁻ , K ⁺ , Mg ²⁺ , Na ⁺ , NO ₃ ⁻ , SO ₄ ²⁻) | 6,225 | 2,437 |
| Organic compounds (Benzene, Toluene, o,p-Xylene, Naphthalene...) | 11 | 730 |

746

747 **Table 2**

748 Main elements of the qualitative profile of VOCs. Quantification was carried out using
749 SPME fibers and GC/MS/FID analysis on the elements released on the third day of
750 drying the paints. Concentrations determined as toluene equivalent from the FID signal.

| Chemicals | VOCwb (mg/m³) | VOCsb (mg/m³) |
|--|-------------------------------------|-------------------------------------|
| Aromatic hydrocarbons (Toluene, Xylene, Ethylbenzene) | - | 2,37 |
| Aliphatic hydrocarbons (Decane, Nonane, Trimethyl cyclohexane...) | - | 148.73 |
| Substituted hydrocarbons (Propylene glycol, 2-butanone, Texanol...) | 6.08 | 32.47 |

751

752 **Legends of the figures**

753 **Fig. 1.**

754 **Experimental design for the exposure of RHE to pollutants**

755 (A) Sequences of treatment for the exposure of RHE to pollutants. (B) Sequences of
756 treatment event for the preconditioning of RHE by the semi-dry/humid airflow before
757 exposure to pollutants. (C) Comparison of the different treatments and controls.

758

759 **Fig. 2.**

760 **Cellular functionality of RHE after exposure to pollutants.**

761 Results of MTT assays performed on RHE exposed to the different pollutants for 24h.
762 n=3 independent experiments in duplicate, except for the negative control and SDS for
763 which n=6 independent experiments with the MTT assay performed in duplicate for
764 each. Conditions are compared to the negative control with * p<0.05, *** p<0.001.

765

766 **Fig. 3.**

767 **Cellular functionality of RHE upon preconditioning by a semi-dry/humid airflow**
768 **followed by exposure to pollutants.**

769 Results of MTT assays performed on RHE preconditioned or not (RH control) by a
770 humid (90% RH) or a semi-dry (45% RH) airflow before being incubated with the
771 different pollutants. n=2 independent experiments with the MTT assay performed in
772 duplicate for each; * p<0.05, ** p<0.01, *** p<0.001.

773

774 **Fig. 4.**

775 **Inflammatory response of RHE after exposure to pollutants.**

776 Profiling of cytokines/chemokines production in RHE exposed or not (negative control)
777 to the different pollutants: (A) PM_m, (B) PM_o, and (C) VOCs and TS. n=1 experiment
778 with the quantification performed in duplicate; * p<0.05, ** p<0.01, *** p<0.001.

779

780 **Fig. 5.**

781 **Inflammatory response of RHE upon preconditioning by a semi-dry/humid airflow**
782 **followed by exposure to pollutants.**

783 Quantification of (A) IL-1 α , (B) IL-8, and (C) RANTES in RHE preconditioned or not
784 (RH control) by the humid (90% RH) or the semi-dry (45% RH) airflow before being
785 incubated with the different pollutants. n=2 independent experiments with the
786 quantification performed in duplicate; * p<0.05, ** p<0.01, *** p<0.001.

Figure 1

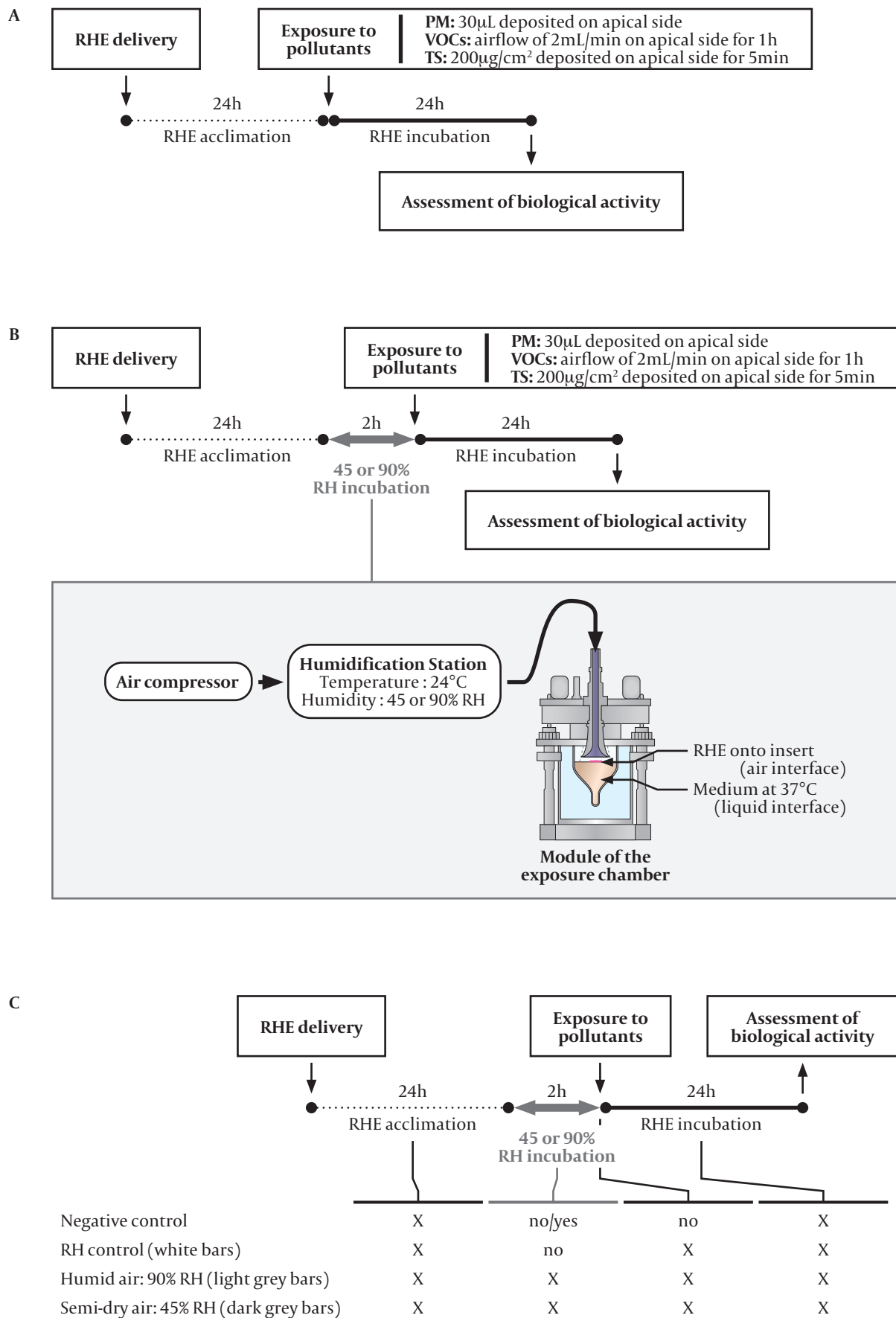


Figure 2

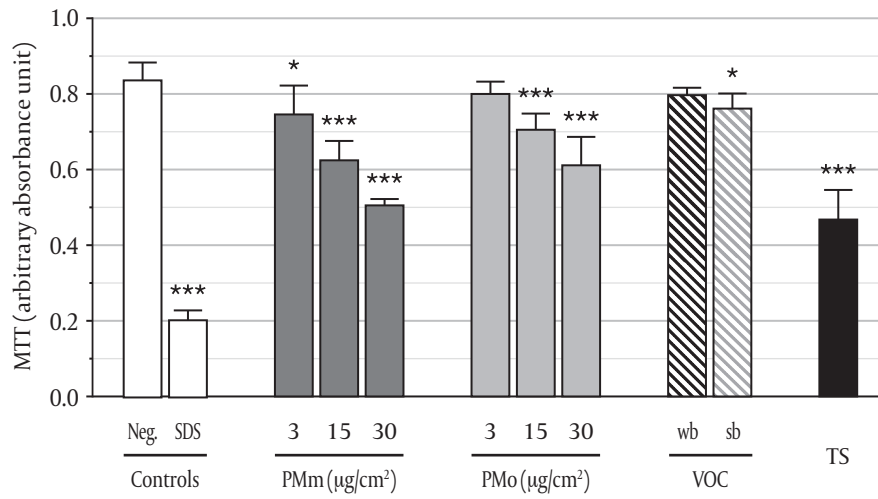


Figure 3

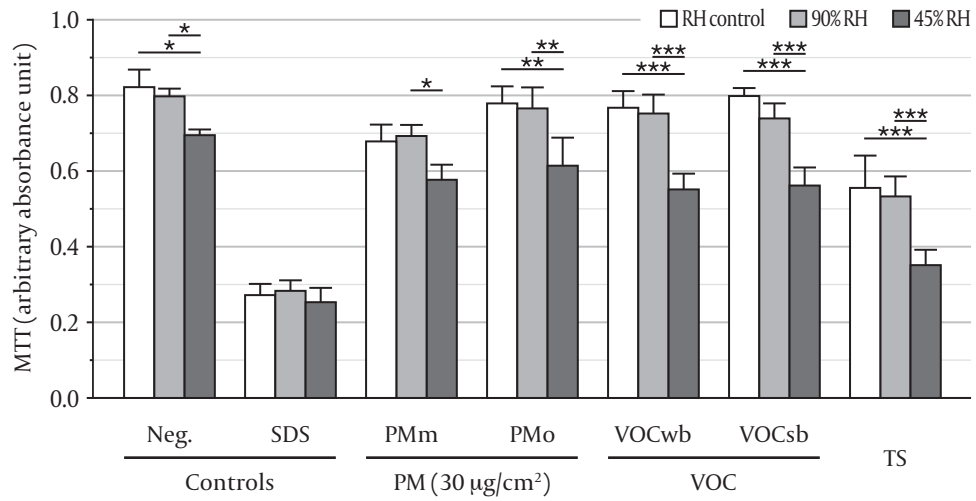


Figure 4

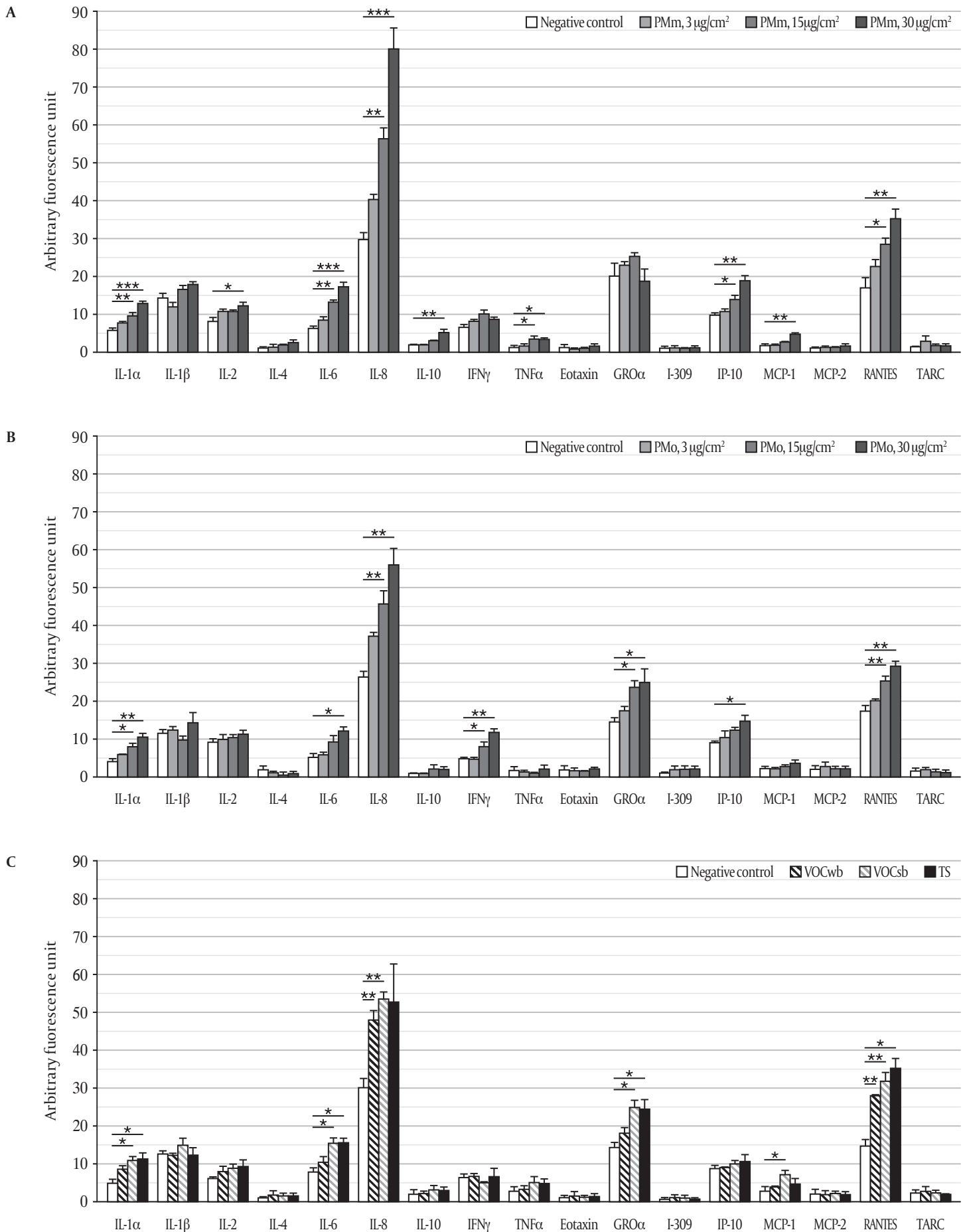
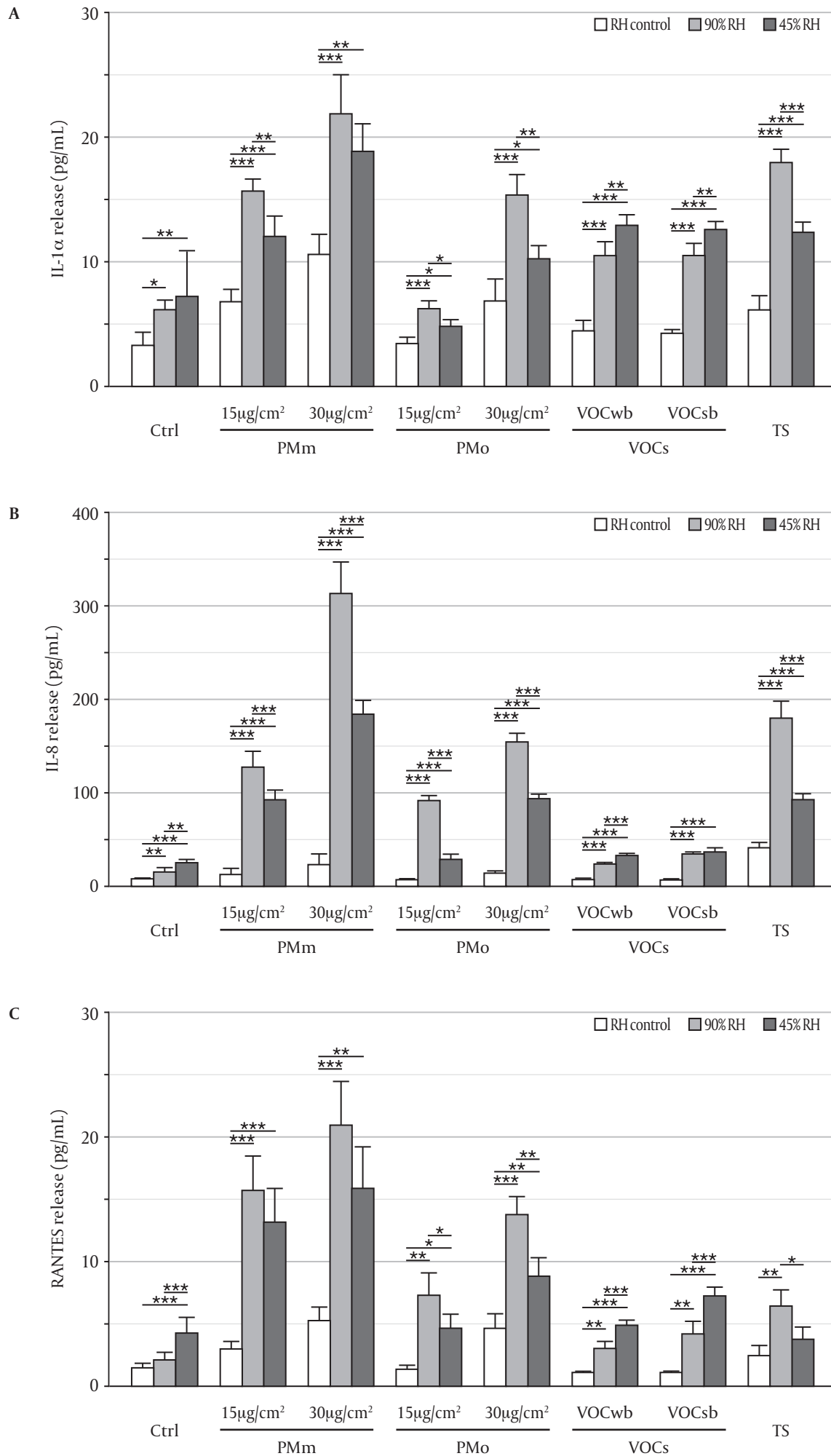
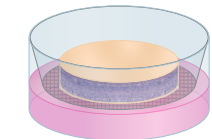


Figure 5

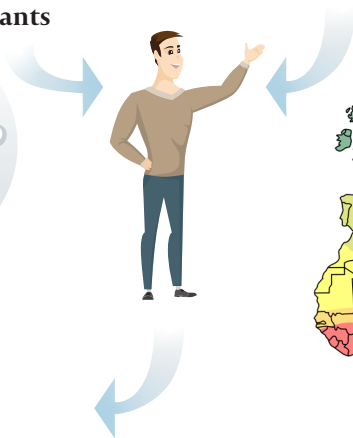




Air pollutants



***In vitro* skin model
Inflammation**



Air humidity

