

Study of gaseous benzene effects upon A549 lung epithelial cells using a novel exposure system

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4 **Study of Gaseous Benzene Effects Upon A549 Lung**
5 **Epithelial Cells Using a Novel Exposure System**
6
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25 **ABSTRACT**

26 Volatile organic compounds (VOCs) are ubiquitous pollutants known to be present in both indoor
27 and outdoor air arising from various sources. Indoor exposure has increasingly become a major
28 cause of concern due to the effects that such pollutants can have on health. Benzene, along with
29 toluene, is one of the main components of the VOC mixture and is a known carcinogen due to its
30 genotoxic effects. The aim of this study was to test the feasibility of an *in-vitro* model to study the
31 short-term effects of exposure of lung cells to airborne benzene. We studied the effects of exposure
32 on DNA and the production of reactive oxygen species (ROS) in A549 cells, exposed to various
33 concentrations of benzene (0.03; 0.1; 0.3 ppm) in gaseous form using a custom designed cell
34 exposure chamber. Results showed a concentration-dependent increase of DNA breaks and an
35 increase of ROS production, confirming the feasibility of the experimental procedure and validating
36 the model for further *in-vitro* studies of exposure to other VOCs.

37

38 **Key words:** *in vitro*; A549; benzene exposure; volatile organic compounds; comet assay; ROS;

39 **1. INTRODUCTION**

40 People spend much of their time indoors where they are continuously exposed to low concentrations
41 of a wide variety of chemicals including volatile organic compounds (VOCs). It has been
42 demonstrated that building materials, furniture and consumer products are a source of low level
43 VOC exposure contributing together with the outdoor air to the exposure of general population
44 (Delgado-Saborit et al., 2011; Wolkoff, 2012). Indoor exposure to VOCs has been reported to cause
45 a number of symptoms ranging from irritation of the respiratory system to sick building syndrome
46 (Brinke et al., 2004; Wang et al., 2013). In addition, VOCs are also reported to contribute to
47 oxidative stress induction via production of reactive metabolites and hence have the potential to
48 damage DNA (Knaapen et al., 2006; Lu et al., 2007; Saint-Georges et al., 2008; Snyder and Hedli,
49 1996; Sørensen et al., 2003a; Wang et al., 2013). Exposure to VOCs such as styrene can also lead to
50 an inflammatory response in the lungs that can then result in oxidative stress (Bönisch et al., 2012;
51 Fubini and Hubbard, 2003; Röder-Stolinski et al., 2008; van Berlo et al., 2010). It has been
52 suggested that other compounds such as benzene and toluene can trigger an inflammatory response,
53 but DNA damage caused by such response has not been supported by solid evidence (Pariselli et al.,
54 2009; Wang et al., 2013). The relationship between exposure to benzene and DNA damage has been
55 extensively studied, especially for occupational exposures, demonstrating that benzene is involved
56 in DNA damage through reactive metabolic intermediates (Hartwig, 2010; Snyder and Hedli, 1996)
57 and generation of reactive oxygen species (ROS) (Barreto et al., 2009). Because of the detailed
58 knowledge of its metabolism, benzene serves as an ideal positive control test compound for the
59 development of new toxicological assays and tests. Furthermore, in several studies of human
60 exposure to benzene at medium and low concentrations (0.001 ppm – 0.03 ppm), a correlation was
61 found between levels of urinary benzene, benzene metabolites and urinary 8-oxo-2'-
62 deoxyguanosine (8-oxo-dG) a biomarker that is widely considered to be associated with ROS
63 related DNA damage and repair (Andreoli et al., 2012; Bagryantseva et al., 2010; Manini et al.,
64 2010).

65 A recent review (Hartwig, 2010) summarised the possible mechanisms through which benzene and
66 its metabolites can cause DNA damage. *In vivo*, after absorption, benzene is metabolized by
67 cytochrome P450 2E1 (CYP2E1) in the liver to produce metabolites including: phenol, catechol,
68 hydroquinone and 1,2,4-trihydroxybenzene. These closed ring metabolites then undergo further
69 metabolism in the bone marrow to form *o*- and *p*-benzoquinone. *p*-Benzoquinone is thought to be
70 the toxic metabolite responsible for myelotoxicity due to its high reactivity and is known to form
71 adducts with proteins and DNA (Linhart et al., 2011; Rappaport et al., 2005). Bone marrow, due to
72 the high rate of cell mitosis and lower DNA repair capacity (Buschfort-Papewalis et al., 2002) is a
73 sensitive tissue for DNA instability, resulting in possible health effects sooner than other tissues.

74

75 All of the phenolic benzene metabolites are chemically active in cells, increasing the oxidative
76 DNA damage, directly or through further metabolization. Therefore, although the main target
77 tissues and the metabolism of benzene have been studied and understood, it is important to develop
78 models to assess the toxicity caused by VOC exposure of other metabolically competent tissues
79 including the lung epithelium, which is a principal route of exposure to benzene and other VOCs.
80 Such models could also be useful to study other VOCs, as currently there is little evidence of any
81 linkage between exposure and DNA damage for other VOC species, even if it has been suggested
82 from studies in animal models and *in-vitro* studies (Sarma et al., 2011a; Singh et al., 2009).

83

84 Currently there are only few detailed studies on the development of *in vitro* models to examine the
85 effects of such pollutants on the lung. Pariselli et al. (2009) developed a method to expose lung cells
86 to various concentrations of benzene and toluene, evaluating some of the effects caused by the
87 pollutants on lung cells growing on permeable supports that allow exposure of cells to gas mixtures,
88 modelling a real life situation of exposure.

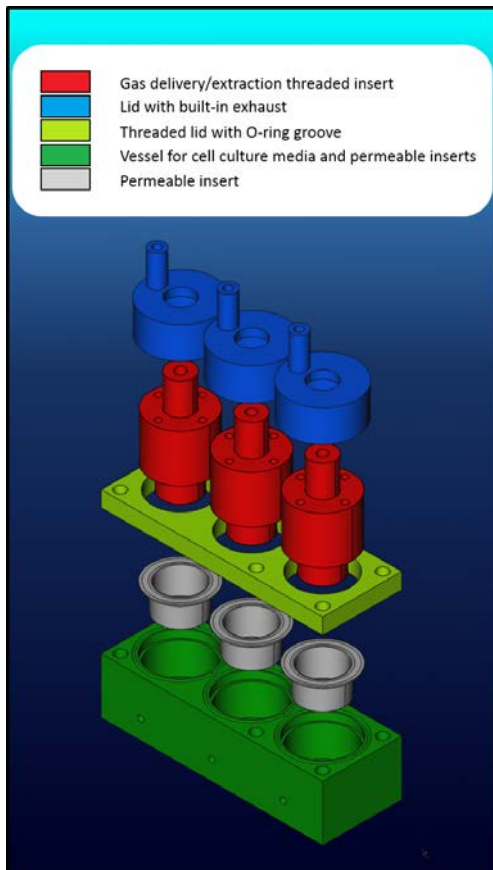
89

90 Although Pariselli et al. (2009) reported interesting results on inflammatory response triggered by
91 VOC exposure and cell viability, no further studies on DNA damage or ROS production were
92 reported deriving from lung epithelium models. We therefore aimed to progress by exploring the
93 feasibility of an air-liquid interface (ALI) *in-vitro* model using lung epithelia cells grown on a
94 permeable membrane. The main focus of this study was on the short-term effects of exposure of
95 lung cells to VOCs with two main endpoints: oxidative stress and DNA damage.

96

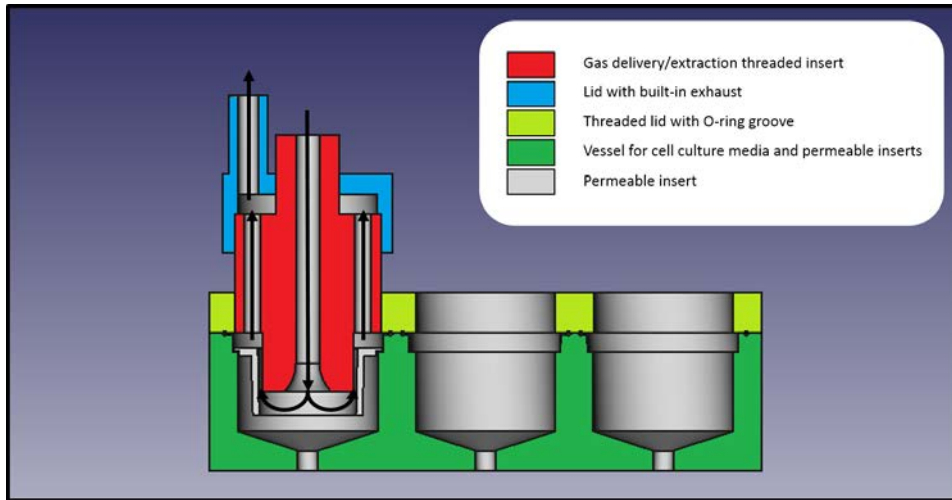
97 2. MATERIALS AND METHODS

98 2.1 Exposure System



99

100 **Figure 1a:** Exploded representation of the exposure vessel with all the part of the assembly.

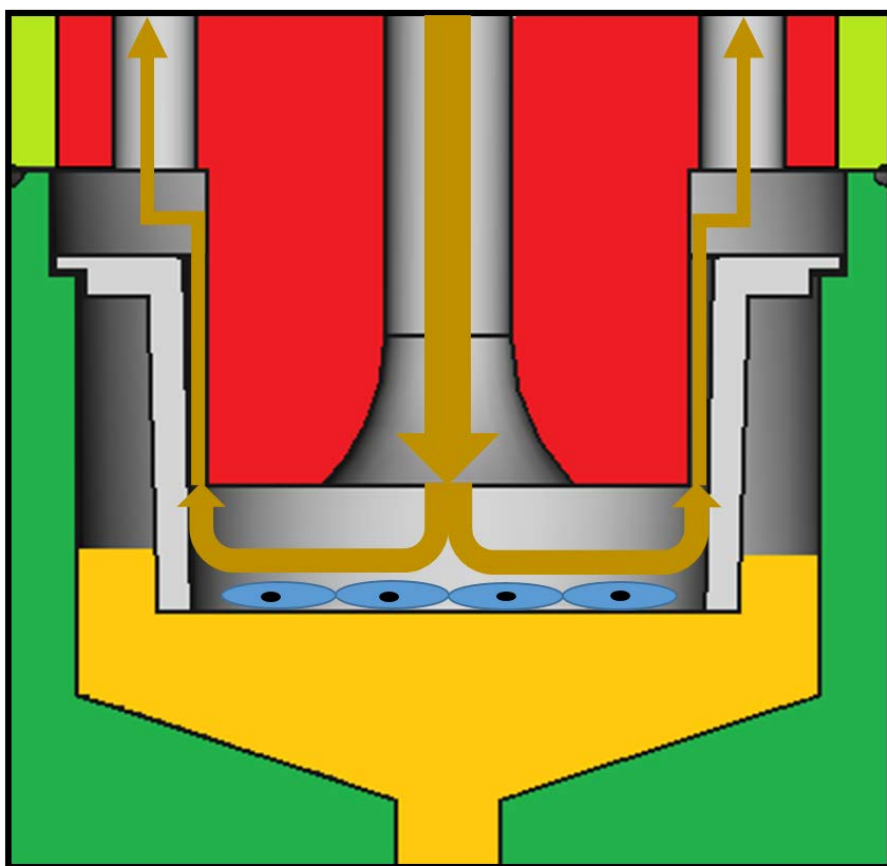


101

102 **Figure 1b:** Cross section of the assembled exposure vessel, arrows indicate the gas flow. In use,
 103 the two vessels to the right are also fitted with the gas delivery system and permeable insert.

104

105 An exposure vessel was custom designed based on the CULTEXs system (Vitrocell, Germany)
 106 described by Pariselli et al. (2009). The system consisted of three wells milled into a polymethyl
 107 methacrylate (PMMA) block, suitable to fit a permeable 6-well insert (Corning Inc., NL) into each
 108 one, and 5ml of media under the inserts (Figure 1a and 1b). The capacity to circulate cell culture
 109 media was included by adding two 5mm holes at the bottom and on the side of each well. These
 110 could be capped if the circulation of the media was not needed.



111

112 **Figure 2:** Detailed cross-section of the gas-cell interface, with the level of the cell culture media
113 indicated in yellow.

114

115 The lid was constructed with threaded holes to fit gas delivery inserts, and the wells were sealed
116 using nitrile O-rings. The gas delivery tubes were designed with a trumpet shape in order to reduce
117 the linear velocity of the delivered gas to reduce mechanical stress to the cells, and to allow
118 maximum mixing and even delivery of the gas along each insert (Figure 2). Each tube was threaded
119 externally to screw into the lid allowing fine adjustments of the distance between the nozzle and the
120 cell layer. The tubes were provided with holes to allow the delivered gas to flow out to the exhaust,
121 providing a continuous flow. The vessel was kept in a gas chromatograph (GC) oven at 37°C during
122 the exposure to maintain the cells at an optimal temperature. The vessel was kept in an incubator at
123 37°C between the exposures. The gas delivery to the cells was regulated by mass flow controllers

124 (MFCs) (Brooks Instrument, NL). One 500 sccm (standard cubic centimeters/minute) MFC was
125 used to regulate the synthetic air (BOC gases, UK) flow, and a 100 sccm MFC was used to regulate
126 the benzene flow (1ppm balanced in nitrogen, BOC gases, UK). A total flow rate of 30 ml/min was
127 used, split between the three wells, with a theoretical flow rate of 10 ml/min in each well.
128 The synthetic air passed through a bubbler heated at 37°C to humidify the air to prevent desiccation
129 of cells, and the pollutant delivery (benzene 1ppm balanced in nitrogen, BOC, UK) was regulated
130 by a second MFC. The two gases were then mixed in a glass mixing chamber hosted inside the GC
131 oven, filtered through a 0.45µm filter and delivered to the cells. The system worked with positive
132 pressure of the exposure gases to ensure sterility.

133

134 **2.2 Cell Culture**

135 A549, epithelial lung carcinoma cells (HPA, 86012804) have been previously used as a model for
136 lung epithelium exposure (Pariselli et al., 2009; Saint-Georges et al., 2008; Shang et al., 2013).
137 Furthermore, this cell line has been reported to express CYP2E1, the cytochrome P450 involved in
138 the metabolism of benzene (Foster et al., 1998; Medinsky et al., 1994; Mögel et al., 2011; Snyder
139 and Hedli, 1996; Sørensen et al., 2003a), and therefore represents a suitable model of study for
140 benzene and VOC toxicology.

141

142 A549 cells were cultured in 6-well plates using RPMI 1640 medium (2.5 ml), containing 25mM
143 HEPES and NaHCO₃ to maintain the pH constant during the exposure period (CO₂ was not
144 contained in the synthetic air). The medium was further supplemented with glutamine (2mM),
145 penicillin (100 U/ml), streptomycin (100 µg/ml), amphotericin B (0.25 µg/ml) and 10% foetal
146 bovine serum (FBS). Cells were passaged regularly using a standard trypsin-EDTA protocol in 6-
147 well plates and split regularly once they reached approximately 90% confluence. For the exposure
148 experiments, approximately 0.3×10^6 cells were seeded into 1.5 ml RPMI 1640 on the collagen
149 coated Transwell inserts with pores of 1µm (Corning, NL) and 2 to 2.5 ml RPMI 1640 were added

150 at the bottom of the well, and the plate was placed in an incubator. Once the cells reached 90%
151 confluence (24–36 hours) they were serum starved for 12 hours by exchanging the medium
152 containing FBS with FBS free medium, to synchronize the cell cycle prior exposure (Campisi et al.,
153 1984). After the exposure, the cells were washed with phosphate buffer solution (PBS) for 5
154 minutes before trypsinization.

155

156 **2.3 Synthetic Air and Benzene Exposure**

157 For each exposure experiment, 3 Transwell inserts cells from the same 6-well plate were exposed
158 for 2 hours to synthetic air (controls), the exposure vessel was then rinsed, washed with 70%
159 ethanol and allowed to dry. ~~and s~~Subsequently, the remaining 3 Transwell inserts were exposed to
160 one of three different concentrations of benzene (0.03 ppm; 0.1 ppm; 0.3 ppm), which were
161 reported to have cytotoxic effects (Pariselli et al., 2009). A first pilot experiment was performed
162 with 3 technical replicates simultaneously exposed to each benzene concentration accompanied by
163 an air exposed control. The obtained results were then confirmed by an independent replicate. The
164 low (0.03 ppm) and high (0.3 ppm) benzene concentrations were further tested by a third
165 independent replicate exposure. Each exposure experiment was accompanied by a set of incubator
166 controls, which consisted in a 6-well plate left for 2 hours in the incubator, where 3 wells contained
167 cells with media (Incubator Media), and 3 wells contained cells with the media removed (Incubator
168 Dry). The removal of the media from the 3 wells was considered the start point of the 2 hours
169 incubation of the incubator controls.

170

171 **2.4 ROS Assay**

172 Reactive oxygen species were assessed by measuring the oxidation of the redox sensitive dye 2',7'-
173 dichlorodihydrofluorescein diacetate (H2DCF-DA, Sigma-Aldrich, UK). Following hydrolysis by
174 intracellular esterases, the resultant H2DCF is unable to leave the cell and is then oxidised by ROS,
175 to form the fluorescent DCF (dichlorofluorescein) molecule. The level of fluorescence is

Comment [d1]: You need to explain how many replicates have you done in the first (old) experiment and second (new) experiment.

When you report the data in the Tables and Figures, you need state how many replicated from which of the two sets of experiments are you reporting information from.

The results that you are not showing in this manuscript (mainly the old data), you have to add it in the Supporting Information, and cross-reference accordingly across the manuscript. This refers to cases like line 252-253.

Comment [d2]: How do you define the incubator control pre- and post-exposure that you report in Figure 3.

176 proportional to the degree of oxidative stress in the cells. Briefly, the cells were preloaded with
177 H2DCF-DA dissolved in the growth medium (10 μ M, final concentration) for 30 minutes. After the
178 loading of the cells, both in the exposed samples and in the incubator controls a first fluorescence
179 reading was taken and marked as pre-exposure. After the treatment (air/benzene exposure or 2
180 hours in the incubator), a second fluorescence reading was taken, marked as post-exposure.
181 DCF fluorescence was quantified before and after exposure using a Tecan Infinite F200 pro plate
182 reader (excitation wavelength: 485 nm, emission wavelength: 535 nm) using I-control V.1.9
183 software. To minimise the exposure of the cells to air, quantification of the fluorescence before the
184 exposure was performed without removing the apical medium from the inserts. Three controls and
185 three exposed samples were analysed. Cells that had not been loaded with H2DCF-DA were used as
186 a negative control and to take into account background levels of fluorescence.

187

188

189 **2.5 Comet Assay**

190 DNA strand breaks were assessed by the alkaline comet assay (Singh et al., 1988). Briefly, after
191 trypsinization, the cells were re-suspended in 150 μ l PBS. 15 μ l of the suspension were added to
192 150 μ l of 0.5% (v/v) warm low melting point agarose (LMPA) and the cell suspension was added to
193 a microscope slide that had been previously coated with 0.5% (v/v) normal melting point agarose
194 (NMPA). After a coverslip was added, the slides were left on an ice-cold tray to allow the agarose
195 to solidify. Once the agarose had solidified, the coverslip was removed and the slides were
196 incubated for 1 hour at 4° C in lysis buffer (2.5 M NaCl, 0.1 M Na₂EDTA, 10 mM Tris base, 1%
197 sodium N-lauryl sarcosinate, 10% DMSO and 1% Triton X-100, pH 10). Next, the slides were then
198 transferred to a horizontal electrophoresis tank containing electrophoresis buffer (NaOH 300 mM,
199 EDTA 1 mM, pH 13.0) and DNA allowed to unwind for 20 minutes. DNA was then subjected to
200 electrophoresis (32 V, 0.8 V/cm) for 20 minutes. The slides after the electrophoresis were
201 transferred to the neutralization buffer (Tris HCl 0.4 M, pH 7.5) and washed 3 times for 5 minutes,

202 followed by 1 wash in H₂O for 5 minutes. Finally, slides were stained with 50 µl of Sybr gold
203 (Invitrogen, 10× solution in neutralisation buffer, UK). Slides were examined at 320× magnification
204 using a fluorescence microscope (Zeiss axiovert 10, Zeiss, UK) fitted with a 515–560 nm excitation
205 filter and a barrier filter of 590 nm. A USB digital camera (Merlin, Allied Vision Technologies,
206 UK) received the images, which were analysed using a personal computer-based image analysis
207 system Comet Assay IV (Perceptive instruments, UK).

208

209 A random sample of at least 300 nuclei on each slide was assessed and categorised into quantifiable
210 or not quantifiable. Unquantifiable nuclei consisted largely of “hedgehogs”, indicative of nuclei
211 where most of the DNA was in the tail and probably represent nuclei from apoptotic and necrotic
212 cells. A minimum of 60 nuclei were quantified per slide (N = 64 - 200). Percent tail DNA (TD %)
213 was chosen to assess the extent of DNA damage in quantifiable cells, as this has been shown to
214 suffer much less from inter-run variation than other Comet parameters because it is largely
215 independent of electrophoresis voltage and run time (Olive and Durand, 2005).

216

217 **2.6 Data Analysis**

218 Data analysis was performed using SPSS Statistics 21 and Microsoft Excel 2013.

219

220 **3. RESULTS**

221 Light microscopy analysis of the cells before and after the exposure demonstrated little mechanical
222 stress and slight drying sustained by the cells due to the airflow, but the following analyses showed
223 that this did not result in overt cell toxicity (data not shown).

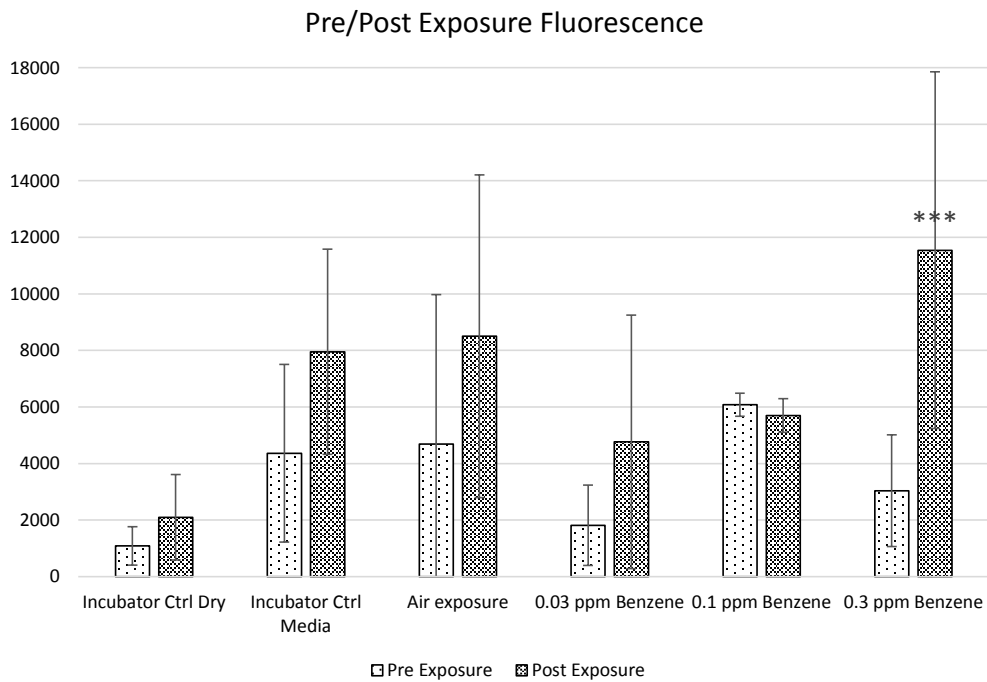
224

225 **3.1 Induction of Oxidative Stress**

226 ~~Cells exposed to the highest concentration of benzene (0.3 ppm) Cells~~ -were analysed for levels of
227 ROS before and after the exposure together with a control that was exposed only to synthetic air

Comment [d3]: Update this sentence, since you have sample ROS in all exposure levels now

228 and a set of incubator controls both with and without apical medium. The results presented in
 229 Figure 3 clearly indicate that cells exposed to 0.3 ppm benzene had elevated levels of intracellular
 230 ROS compared to controls as assessed by the fluorescein oxidation assay. The presented results are
 231 based on two independent replicates (each including three technical replicates) for 0.03 ppm and 0.3
 232 ppm benzene, and a single measurement of three technical replicates for 0.1 ppm benzene.
 233 Incubator control results are based on 5 independent replicates. The means were compared using
 234 ANOVA with Bonferroni post-hoc comparisons. The only statistically significant difference
 235 between the pre and post exposure was observed for the 0.3 ppm benzene exposed cells ($p < 0.001$).
 236



237
 238 **Figure 3:** Summary of the DCF fluorescence measurements before and after exposure. Error bars
 239 represent standard deviation. (*** indicates a statistically significant difference between the pre and the post exposure.
 240
 241
 242 A generalized increase of fluorescence was observed in all the treatments, including the incubator
 243 controls, suggesting a baseline production of ROS in normal cell metabolism. Unfortunately, in the

Comment [d4]: Something seems rather odd in the exposure of 0.1 ppm. It doesn't follow the pattern of higher ROS in the post exposure, which is clearly observed, although not statistically significant in all the tests, except for 0.3 ppm, where it is statistically significant.

Comment [d5]: How many replicates does this figure represent?

244 case of 0.1 ppm benzene exposure, the pre-exposure condition showed a high reading, most likely
 245 due to media background fluorescence. These findings are comparable with previously published
 246 data (Pariselli et al., 2009). Although further tests need to be performed, treatment with benzene
 247 shows an oxidative effect in the cells, which could be related to either an inflammatory response to
 248 benzene itself, or more probably to oxidising metabolites such as benzoquinones (Snyder and Hedli,
 249 1996).

Comment [d6]: Add a reference supporting this statement

251 3.2 Induction of DNA Strand Breaks

252 Following exposure of cells to both low (0.03 ppm) and medium (0.1 ppm) benzene concentrations,
 253 the incidence of highly damaged “hedgehog” cells was below 15% of the total number of cells
 254 counted. In contrast the number of not quantifiable nuclei was increased at higher benzene
 255 concentrations (23–60% of unquantifiable nuclei, N=300). The high frequency of “hedgehogs” at
 256 the highest concentration of benzene exposure tested (0.3 ppm) made DNA damage quantification
 257 difficult and is indicative of direct benzene cytotoxicity to cells at this concentration of benzene
 258 exposure.

260 **Table 1:** Descriptive statistics of the Comet assay data (% tail intensity).
 261 * indicates a statistically significant difference with the control.

	N (Cells)	Mean	Median	Standard Deviation	Variance	H (Variance/Mean)
Incubator Controls (Media)	1550	4.52	0.74	9.40	70.98	20.61
Incubator Controls (Dry)	1376	6.73	3.40	11.80	135.26	18.98
Controls	1028	7.40	3.15	11.60	147.82	20.77
0.03 ppm benzene	314	11.49	3.21	15.58	243.83	21.26
0.1 ppm benzene	318	16.02*	5.53*	21.28	456.49	28.37
0.3 ppm benzene	375	12.27*	5.13*	16.90	303.75	23.29

Comment [d7]: How many replicates of which experiment are present here?

262
 263 The % tail intensity was used as a metric to quantify DNA damage in the cells. Experimental data
 264 were pooled from 59 controls and all of the one of the independent 3 replicates of each exposure,
 265 which consisted of 3 technical replicates for each exposure, and the findings are summarised in

Comment [d8]: Do you mean the technical replicate or the exposure replicate?

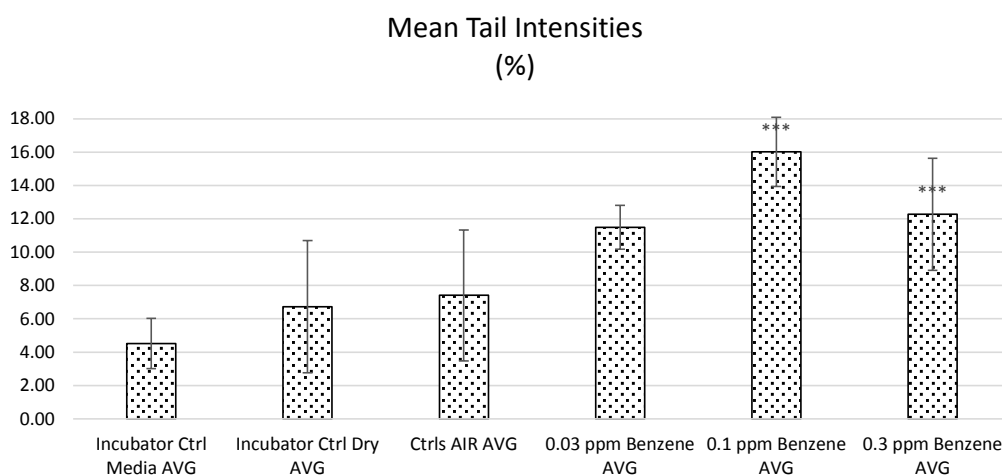
266 Table 1 and Figures 4 and 5. Each exposure event was compared with the relative control. The
267 reported data refers to a single exposure experiment and the relative controls. Two independent
268 replicates were performed for the ~~experiment~~0.03 ppm and 0.3 ppm exposure, obtaining similar
269 results (~~data not shown~~Supplementary material, Table 1). Differences were observed between the
270 absolute values of the tail intensities, however the ratios between the exposed and the control cells
271 were found to be similar between the replicates. ~~A paired-samples t test showed a high coefficient
272 of correlation between the ratios (R=0.821-0.951), although due to the limited amount of replicates
273 and data points the test was not statistically significant (p=0.200-0.387)~~The ratios were compared
274 by an Kruskal-Wallis independent samples test, which retained the null hypothesis of the samples
275 having the same distribution (p=0.102). An independent samples median test also retained the null
276 hypothesis, suggesting that the medians of the ratios are similar (p=0.354). The observed
277 differences of the absolute values between the independent replicates are likely due to different
278 starting conditions of the cells. Tail intensities of each exposed sample were compared with its
279 relative air exposed control using Friedman's 2-way ANOVA by ranks. The only statistically
280 significant differences were observed between the samples exposed to 0.1 ppm and 0.3 ppm
281 benzene and their relative controls. No statistically significant difference was observed between air
282 exposed controls and incubator controls under any condition.

283 A clear concentration-dependent induction of DNA strand breaks following the exposure to benzene
284 (0.03–0.3 ppm) was observed as assessed by the exposed/control ratio of mean tail intensity (Figure
285 6). ~~In general, due to the high amount of "hedgehogs", the cells exposed to 0.3 ppm benzene,
286 showed a decreased amount of DNA damage compared to the cells exposed to 0.1 ppm benzene.~~
287 Linear regression analysis showed a significant correlation between the level of benzene exposure
288 and the extent of DNA damage when the value was normalized against the relative controls
289 ($R^2=0.718914$). An increase of DNA damage was observed in all the exposures, however a
290 statistically significant difference with the control was observed only for 0.1 ppm and 0.3 ppm
291 benzene concentrations (Figure 4). Figure 5 represents the pooled data of each exposure experiment

Comment [d9]: Add a cross-reference of where this data can be found in the SI

Comment [d10]: Between the replicates of the same exposure, or between exposures?

292 in a scatter plot. Data was plotted to evaluate the increase of dispersion of the readings with higher
 293 benzene exposure, indicating a generalized increase in DNA damage related to the concentration of
 294 airborne benzene. Importantly, we observed a statistically significant increase in levels of DNA-
 295 strand breaks in cells exposed to 0.1 ppm benzene were there was no evidence of direct cytotoxicity
 296 to the cells.
 297

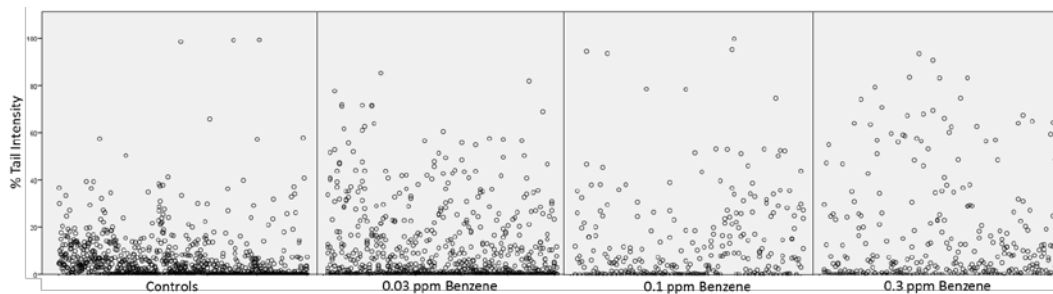


298 **Figure 4:** Mean tail intensity (%) of the control and exposed cells. Error bars represent the standard
 299 deviation of the means.
 300 (***) indicates a statistically significant difference between the exposed sample and their relative
 301 controls.
 302
 303

Comment [d11]: How many replicates of which experiment are present here?

304 The coefficient of dispersion (H) (Tice et al., 2000), expressed as the ratio of variance/mean, was
 305 also calculated to further evaluate the data (Table 1). H is an accepted parameter used to express the
 306 dispersion of the Comet data and is sensitive to a large DNA damage response in a small proportion
 307 of cells and is also less affected by inter-experimental variability. All of these parameters were
 308 consistent with a concentration-dependent increase in DNA strand breaks following exposure of
 309 cells to benzene.

310

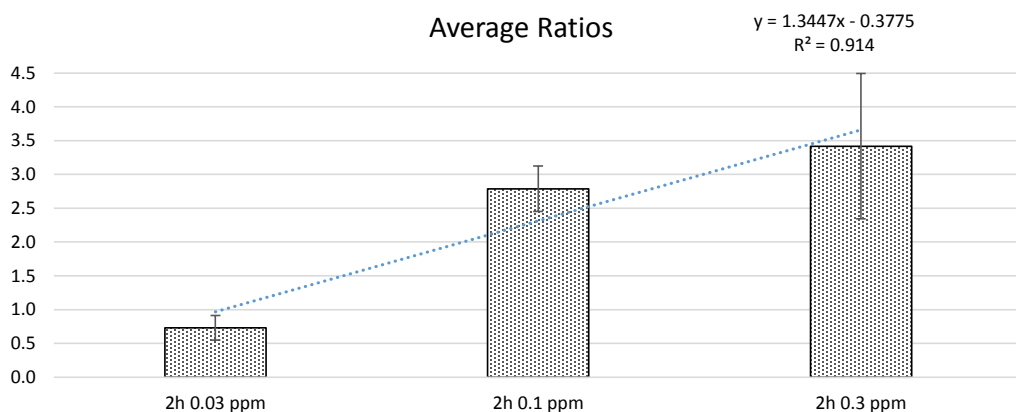


311 **Figure 5:** Graphical representation of the % tail intensities measured in the Comet assay as a
 312 function of benzene concentration. The figure includes 5 independent replicates for the controls, 2
 313 independent replicates for 0.03 and 0.3ppm benzene, and a single independent replicate for 0.1ppm
 314 benzene.
 315
 316

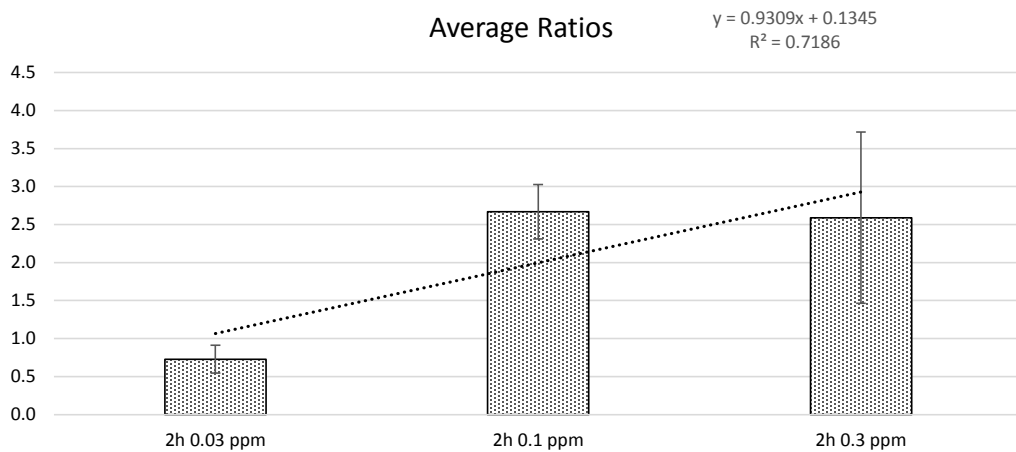
Comment [d12]: How many replicates of which experiment are present here?

317 To minimise the effects of inter-experiment variability, the ratio of mean % tail intensity between
 318 the treated cells and the controls of the same exposure experiment were compared. This enhanced
 319 the difference between the low level exposure (2h 0.03 ppm) and the higher levels. The reported
 320 ratios (Figure 6) are obtained by averaging the ratio of exposed/control mean tail intensity (%) of
 321 each independent replicate. Interestingly, the difference between the ratios of the two higher
 322 conditions was smaller than the difference in the ratios observed between the 0.03 ppm and 0.1 ppm
 323 benzene, as shown in Figure 6. Moreover, the higher concentration showed a lower ratio than 0.1
 324 ppm exposed cells, with a higher variability. This is likely due to the higher amount of
 325 unquantifiable cells in the highest benzene ~~concentration~~concentration, which made the
 326 quantification difficult.

327



328



329

Figure 6: Average ratio between mean % tail intensities of treated cells and each of the relative controls of 3 independent replicates for 0.03 ppm and 0.3ppm and of 2 independent replicates for 0.1 ppm. Error bars represent standard deviation between the ratios of each replicate.

330

331

332

333

4. DISCUSSION

334

The aim of this pilot study was to develop an ALI *in-vitro* system to study the short-term effects of airborne exposure of lung cells to toxic chemicals in a physiologically relevant model. Although carcinoma cells were used instead of primary cells, A549 cells are commonly used as a toxicological model for lung tissue. Moreover, they represent a valuable model as they can reproduce at cellular level the aromatic VOCs metabolic pathway through the cytochrome P450 2E1/CYP2E1, which is a multi-organ pathway in a complete organism (Bois et al., 1996; Hartwig,

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338

339

Comment [d13]: How many replicates of which experiment are present here?

Comment [d14]: Define

340 2010; Snyder and Hedli, 1996). Benzene was chosen as a test pollutant due to its known genotoxic
341 effects. The benzene concentrations used in this work lie between typical ambient air and
342 occupational exposure levels. Delgado-Saborit et al. (2009; 2011) report personal exposure
343 concentrations measured in the UK of 0.15-30.2 $\mu\text{g m}^{-3}$ (0.05-9.3 ppb) while in Saudi Arabia,
344 ambient air benzene concentrations ranged from 0.09-1.1 ppb (Alghamdi et al., 2014) and in 43
345 Chinese cities varied between 0.7-10.4 ppb (Barletta et al., 2005). These compare with
346 concentrations in this study of 0.03-0.3 ppm (30-300 ppb), and the European Union ambient air
347 quality standard of 5 $\mu\text{g m}^{-3}$ (1.5 ppb). On the other hand, the occupational exposure limit for
348 benzene recommended by both NIOSH (US) and HSE (UK) is 1 ppm time-weighted average over
349 an 8-hour shift.

350

351 As previously reported, a limitation of many *in vitro* cellular models of lung toxicity is that cells are
352 exposed to test chemicals dissolved in cell culture media (Pariselli et al., 2009). This is
353 physiologically unrealistic, and furthermore the media itself can have a matrix effect, and the uptake
354 and the interaction of the pollutants with the cells does not model a real life situation (Ritter et al.,
355 2001). The exposure vessel custom designed and used in this study proved to be a useful and
356 reliable tool to evaluate the effect of benzene on cultured lung A549 cells. It also represents a more
357 physiologically relevant model than exposure of cells to benzene dissolved in cell culture media.
358 Development of permeable cell culture inserts has allowed the development of models whereby
359 lung epithelial cells can be grown in a monolayer and the apical medium can be removed during the
360 exposure to airborne chemicals, thus better modelling a lung epithelium and allowing exposure of
361 cells to controlled atmospheres. This method of exposure is much closer to an *in-vivo* situation,
362 providing a more realistic model for exposure studies. For logistical reasons, the gas flow rate was
363 higher than previously reported in the literature (10 ml/min vs. 2 ml/min). However, this variable
364 did not affect the performance of the exposure vessel or the cells negatively, as shown by the
365 comparisons between incubator controls and synthetic air exposed controls (Figure 3 and 4).

366 However, some mechanical stress was observed in the cells at the centre of the airflow by optical
367 microscopy analyses, which can be solved in future experiments by reducing the flow rate as
368 suggested by Pariselli et al. (2006). A longer exposure (4h) of cells to synthetic air was also tested,
369 but the majority of the cells did not survive during the experiment. Overall, our findings confirmed
370 the feasibility of the experiments and the reliability of the model.

371

372 Measurement of ROS levels using the DCF assay showed a significant increase of oxidised
373 fluorescein in cells exposed to 0.3 ppm benzene for 2 hours. This finding is in accordance to
374 previously reported data that has linked benzene exposure with inflammation and ROS production
375 (Barreto et al., 2009; Mögel et al., 2011; Pariselli et al., 2009; Sørensen et al., 2003b; Wang et al.,
376 2013). Furthermore, this data is consistent with a previous report by Mögel et al. (2011) that A459
377 cells express ~~cytochrome-P450~~CYP-2E1, that is involved in the benzene metabolism and ROS
378 production. Intracellular ROS production could be related to the production of oxidising metabolites
379 of benzene such as benzoquinone as suggested by Hartwig (2010).

380

381 Metabolism of benzene has also been linked to DNA damage due to reactive benzene metabolites
382 and ROS generation, which was confirmed in the current study by the results of the Comet assay.
383 Figure 5 shows the direct correlation between the benzene concentration and DNA damage, and
384 importantly there is evidence of DNA strand breaks at concentrations that were not directly toxic to
385 the cells. One of the possible mechanisms of action could be through the known reactive benzene
386 metabolite *p*-benzoquinone. One of its cellular targets is topoisomerase-II, which is inhibited,
387 generating DNA double strand breaks (DSB) which are then repaired by homologous recombination
388 (HR) or non-homologous end-joining (NHEJ). NHEJ is thought to be more error prone than HR,
389 however DSB damage can lead to DNA aberrations by base deletions or translocations.
390 Furthermore, the metabolism of benzene through redox cycling and generation of ROS is proposed
391 as another main source of DNA damage. When hydroquinone or catechol are oxidised in the

392 presence of oxygen, superoxide (O_2^-) is formed, which is then transformed into H_2O_2 by superoxide
393 dismutase. H_2O_2 is not responsible for DNA damage directly, but it increases the oxidative potential
394 of the cell, and in the presence of transition metals ions, hydroxyl radical ($\bullet OH$) is formed, which
395 reacts with lipids, proteins and DNA. $\bullet OH$ is responsible for the formation of 8-oxo-dG and other
396 nucleobase alterations due to oxidation (Halliwell and Aruoma, 1991). H_2O_2 production is also
397 linked to an inflammatory response of which, as stated above, VOC exposure has been reported to
398 be a trigger.

399

400 In addition to non-toxic concentrations, relatively high concentrations of benzene (compared to the
401 concentrations that can be found in everyday life), which have been reported to have cytotoxic
402 effects as well as genotoxic effects, were also studied. In the current study, we saw evidence of
403 benzene cytotoxicity following exposure of cells for 2h at a concentration of 0.3 ppm as indicated
404 by the fact that a large number of cells nuclei were not quantifiable by the Comet assay, but
405 appeared instead as “hedgehogs”. Further evidence of that effect is represented by the tail intensity
406 data normalised against the controls (Figure 6) and the H value decreasing at the higher
407 concentration. In the 0.3 ppm exposure a significant fraction of nuclei in the Comet assay appeared
408 as “hedgehogs” and were classified as unquantifiable (23-60% of unquantifiable nuclei, N=300 per
409 slide), while at lower levels of benzene, the number of “hedgehogs” was negligible. Although the
410 significance of hedgehog nuclei in the Comet assay is not entirely clear, they may represent nuclei
411 derived from either apoptotic or necrotic cells, although other studies have shown that cells
412 sustaining extensive DNA damage can survive and repair the damage taken (Collins, 2004). These
413 results could provide a further insight on the interpretation of the data reported by Pariselli et al.
414 (2009). In that study, the tests were performed after incubating the cells in complete medium for
415 24h after the exposure, allowing the cells to respond to the pollutants and their effects. It is known
416 that large amount of DNA damage and bulky adducts can trigger apoptotic response (Roos and
417 Kaina, 2006), and furthermore benzene has been shown to be capable of inducing apoptosis by

418 production of ROS and DNA damage in leukaemia cells (Sarma et al., 2011b). In our study, cells
419 were analysed immediately after 2h exposure, not allowing sufficient time for the apoptotic
420 response to happen, therefore there is the possibility that most of the “hedgehogs” we observed in
421 the higher benzene exposure could eventually undergo apoptosis.

422

423 The Comet assay data confirmed the genotoxic activity of benzene not only in its widely
424 acknowledged target organs (bone marrow), but also in metabolically competent cells derived from
425 lung epithelial cells. Although the mechanism of action was not fully elucidated, generation of ROS
426 arising from benzene exposure was observed, as well as an association between exposure to
427 benzene and DNA damage.

428

429 In conclusion, with this pilot study we have confirmed that A549 cell line represents a valid model
430 to test exposure and DNA damage arising from airborne exposure to benzene. Although the
431 metabolism of benzene *in vivo* is more complex and involves different tissues, A549 cells appear to
432 produce a response that is compatible to the one found in the target organs of those compounds *in*
433 *vivo*. Further metabolomic and proteomic studies would be needed to confirm the theory, and
434 further studies with different endpoints will be needed in order to have a better understanding of
435 benzene metabolism and its correlation with DNA damage. Furthermore, the results obtained by
436 studying a well known carcinogen confirmed the validity of this model for analysing not only the
437 effects of exposure of lung cells to benzene, but also opens the way for analysing other common
438 VOC with the same procedure, to assess the potential DNA damage caused by exposure.

439

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443

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564

565

566 **TABLE LEGEND**

567

568 Table 1: Descriptive statistics of the Comet assay data (% tail intensity).

569 * indicates a statistically significant difference with the control.

570

571

572

573 **FIGURE LEGENDS**

574

575 Figure 1a: Exploded representation of the exposure vessel with all the part of the assembly.

576

577 Figure 1b: Cross section of the assembled exposure vessel, arrows indicate the gas flow. In use,
578 the two vessels to the right are also fitted with the gas delivery system and permeable
579 insert.

580

581 Figure 2: Detailed cross-section of the gas-cell interface, with the level of the cell culture
582 media indicated in yellow.

583

584 Figure 3: Summary of the DCF fluorescence measurements before and after exposure. Error
585 bars represent standard deviation

586 *** indicates a statistically significant difference between the pre and the post
587 exposure.

588

589 Figure 4: Mean tail intensity (%) of the control and exposed cells. Error bars represent the
590 standard deviation.

591 *** indicates a statistically significant difference between the exposed sample and
592 their relative controls.

593

594

595 Figure 5: Graphical representation of the % tail intensities measured in the Comet assay as a
596 function of benzene concentration.

597

598 Figure 6: Average ratio between mean % tail intensities of treated cells and each of the relative
599 controls of 3 independent replicates. Error bars represent standard deviation.

600