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Johanna Lepeule, Isabelle Pin, Anne Boudier, Joane Quentin, Sarah Lyon-Caen, Karine Supernant, Emie Seyve, Ryan Chartier, Remy Slama, Valérie Siroux

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1 **Pre-natal exposure to NO<sub>2</sub> and PM<sub>2.5</sub> and newborn lung function: an approach based on repeated**  
2 **personal exposure measurements**

3  
4 Johanna Lepeule<sup>1</sup>, Isabelle Pin<sup>1,2</sup>, Anne Boudier<sup>1,2</sup>, Joane Quentin<sup>1,2</sup>, Sarah Lyon-Caen<sup>1</sup>, Karine  
5 Supernant<sup>1</sup>, Emie Seyve<sup>1</sup>, Ryan Chartier<sup>3</sup>, Remy Slama<sup>1</sup>, Valérie Siroux<sup>1</sup> and the SEPAGES study group

6  
7 <sup>1</sup> Université Grenoble Alpes, Inserm, CNRS, IAB, Team of Environmental Epidemiology Applied to  
8 Development and Respiratory Health, 38000 Grenoble, France.

9 <sup>2</sup> Pediatric Department, Grenoble Alpes University Hospital, Grenoble, France

10 <sup>3</sup> RTI International, Research Triangle Park, NC, USA

11  
12 The SEPAGES study group includes E. Eyriey, A. Licinia, A. Vellement (Groupe Hospitalier Mutualiste,  
13 Grenoble), I. Pin, S. Bayat, P. Hoffmann, E. Hullo, C. Llerena (Grenoble Alpes University Hospital, La  
14 Tronche), X. Morin (Clinique des Cèdres, Echirolles), A. Morlot (Clinique Belledonne, Saint-Martin  
15 d'Hères), J. Lepeule, S. Lyon-Caen, C. Philippat, I. Pin, J. Quentin, V. Siroux, R. Slama (Grenoble Alpes  
16 University, Inserm, CNRS, IAB).

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19 **CORRESPONDING AUTHOR**

20 Johanna Lepeule

21 Institute for Advanced Biosciences (IAB)

22 INSERM U1209

23 Site Santé, Allée des Alpes

24 38700 La Tronche, France

25 +33476549466

26 [Johanna.lepeule@univ-grenoble-alpes.fr](mailto:Johanna.lepeule@univ-grenoble-alpes.fr)

27

## 28 **ABSTRACT**

### 29 Context

30 While strong evidence supports adverse effects of pre-natal air pollution on child's lung  
31 function, previous studies rarely considered fine particulate matter (PM<sub>2.5</sub>) or the potential  
32 role of offspring sex and no study examined the effects of pre-natal PM<sub>2.5</sub> on the lung function  
33 of the newborn.

### 34 35 Aim

36 We examined overall and sex-specific associations of personal pre-natal exposure to PM<sub>2.5</sub>  
37 and nitrogen (NO<sub>2</sub>) with newborn lung function measurements.

### 38 39 Methods

40 This study relied on 391 mother-child pairs from the French SEPAGES cohort. PM<sub>2.5</sub> and NO<sub>2</sub>  
41 exposure was estimated by the average concentration of pollutants measured by sensors  
42 carried by the pregnant women during repeated periods of one week. Lung function was  
43 assessed with tidal breathing analysis (TBFVL) and nitrogen multiple breath washout (N<sub>2</sub>MBW)  
44 test, performed at 7 weeks. Associations between pre-natal exposure to air pollutants and  
45 lung function indicators were estimated by linear regression models adjusted for potential  
46 confounders, and then stratified by sex.

### 47 48 Results

49 Mean exposure to NO<sub>2</sub> and PM<sub>2.5</sub> during pregnancy was 20.2 µg/m<sup>3</sup> and 14.3 µg/m<sup>3</sup>,  
50 respectively. A 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub> maternal personal exposure during pregnancy was  
51 associated with an adjusted 2.5 ml (2.3%) decrease in the functional residual capacity of the  
52 newborn (*p*-value=0.11). In females, functional residual capacity was decreased by 5.2 ml  
53 (5.0%) (*p*=0.02) and tidal volume by 1.6 mL (*p*=0.08) for each 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub>. No  
54 association was found between maternal NO<sub>2</sub> exposure and newborns lung function.

### 55 56 Conclusions

57 Personal pre-natal PM<sub>2.5</sub> exposure was associated with lower lung volumes in female  
58 newborns, but not in males. Our results provide evidence that pulmonary effects of air  
59 pollution exposure can be initiated in utero. These findings have long term implications for  
60 respiratory health and may provide insights into the underlying mechanisms of PM<sub>2.5</sub> effects.

### 61 62 63 **Key words**

64 Newborn, lung function, personal exposure, air pollution, pregnancy

### 65 66 67 68 **Introduction**

69 Although the maturation of the lungs is not complete until late adolescence, the lungs  
70 undergo a series of well-orchestrated events that begins early in utero through complex  
71 processes involving interrelated systems (e.g. neuroendocrine, immune autonomic) such that  
72 they are ready to function following birth (Pinkerton and Joad 2006; Schittny 2017).  
73 Intrauterine and early post-natal periods are windows of time that are vulnerable to

74 environmental exposures because of the high growth rate of organs combined with immature  
75 detoxification systems. Growing evidence indicates that exposure to traffic-related air  
76 pollutants during the developmental period has adverse effects on child respiratory health,  
77 including reported associations between fine particulate matter with an aerodynamic  
78 diameter less than 2.5 microns (PM<sub>2.5</sub>), coarse particulate matter with an aerodynamic  
79 diameter less than 10 microns (PM<sub>10</sub>), and nitrogen dioxide (NO<sub>2</sub>), with respiratory symptoms  
80 and lung function (Cai et al. 2020; Garcia et al. 2021; Korten et al. 2017; Schultz et al. 2017).

81  
82 Pre-natal exposure to traffic-related air pollutants has been associated with lung function  
83 (Bose et al. 2018; Bougas et al. 2018; Cai et al. 2020; He et al. 2019; Latzin et al. 2009; Lee et  
84 al. 2018; Milanzi et al. 2018; Morales et al. 2015; Mortimer et al. 2008; Usemann et al. 2019).  
85 However, most of these studies have relied on spirometry tests conducted after the child has  
86 reached 5 years of age. The importance of early lung development on the lifelong lung  
87 trajectory, including lung growth and peak lung function in early adulthood, is well established  
88 (Schultz et al. 2018; Stern et al. 2007) and measuring newborn lung function using  
89 noninvasive techniques has proven feasible and relevant to the field (Latzin et al. 2009). Fine  
90 traffic-derived particles can cross the placenta and have direct or indirect effects on the  
91 developing fetus (Bongaerts et al. 2020, 2021; Nääv et al. 2020), but most of the literature  
92 has focused on pre-natal ambient NO<sub>2</sub> and PM<sub>10</sub>, with limited data associating lung  
93 development and PM<sub>2.5</sub> exposures (Jedrychowski et al. 2010; Lee et al. 2018; Milanzi et al.  
94 2018). Another limitation lies in the use of ambient models based upon residential addresses  
95 to estimate the exposures of study participants. This approach does not account for various  
96 microenvironments visited by the participant nor for time spent indoors, leading to the  
97 possibility of substantial exposure misclassification. To our knowledge, no study has examined  
98 associations of personal pre-natal exposure to PM<sub>2.5</sub> and NO<sub>2</sub> with lung function of the  
99 newborn.

100  
101 Identifying determinants of early infant lung function has long term implications for  
102 respiratory health and might further help in developing preventive programs for at-risk  
103 children. Recent studies have underlined the possibly sex-specific nature of respiratory effects  
104 of pre-natal air pollutants exposure (Bose et al. 2018; Leon Hsu et al. 2015; Schultz et al.  
105 2017). Human and animal studies show differences in lung growth and airway development  
106 between male and female fetuses lending support to differential responses to environmental  
107 toxicants (Bolte et al. 2021; Carey et al. 2007; Liptzin et al. 2015; Torday et al. 1981).

108  
109 To address these research gaps, we examined the impact of pre-natal PM<sub>2.5</sub> and NO<sub>2</sub>, as  
110 measured by repeated personal sampling, on lung function of the newborn in a prospective  
111 couple-child cohort. We hypothesized that lung function responses to air pollutants exposure  
112 would differ between males and females.

113  
114

## 115 **Materials and methods**

### 116 Study population

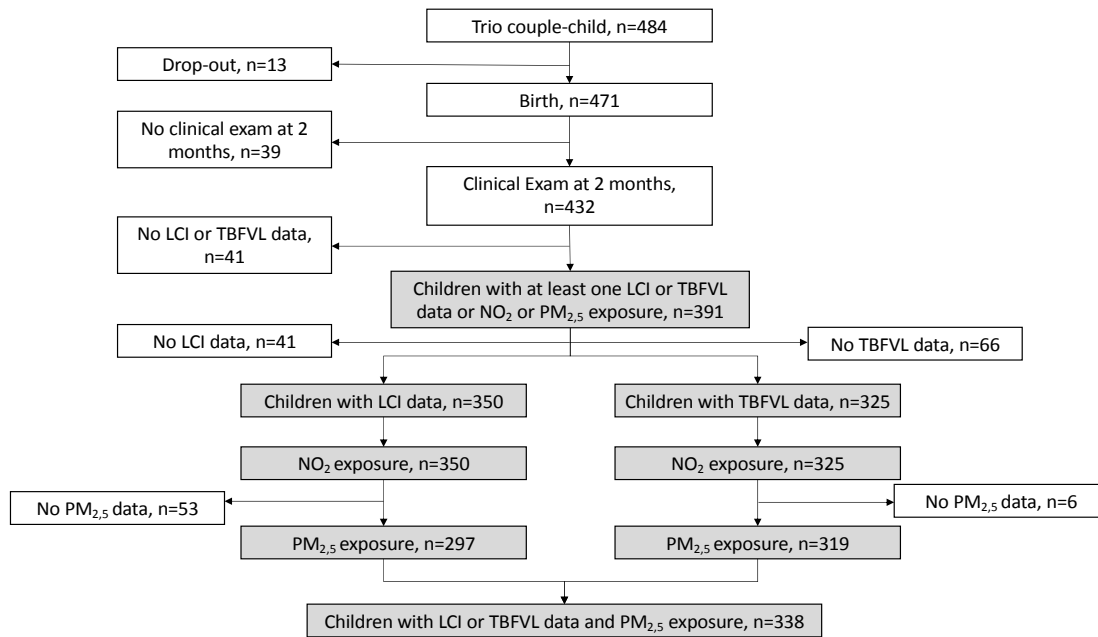
117 This study relied on the French prospective SEPAGES (Suivi de l'Exposition à la Pollution  
118 Atmosphérique durant la Grossesse et Effet sur la Santé) couple-child cohort, that recruited  
119 484 pregnant women from the Grenoble metropolitan area, from 2014 to 2017 (Lyon-Caen et  
120 al. 2019). The inclusion criteria were being pregnant by less than 19 gestational weeks, older

121 than 18 years old, having a singleton pregnancy, being affiliated to the French national  
122 security system, planning to deliver in one of the four maternity clinics of Grenoble and living  
123 in the study area. Questionnaires, interviews and clinical examinations during and after  
124 pregnancy were used to collect sociodemographic and medical information on the children  
125 and parents. For the purposes of our study, we focused on 391 mother-child pairs with both  
126 exposure to air pollutants during pregnancy and child lung function assessments at 2 months  
127 (Figure 1). The SEPAGES cohort received approval from the Ethics Committee (CPP) Sud-Est V,  
128 the National Commission on Informatics and Liberty (CNIL). Both the mother and the father of  
129 the expected child gave written informed consent prior to inclusion.

130

131

132 Figure 1: Flowchart for the selection of the study population



133  
 134 TBFVL: Tidal Breathing Flow Volume Loops; LCI: Lung Clearance Index; NO<sub>2</sub>: Nitrogen dioxide;  
 135 PM<sub>2.5</sub>: Particulate matter with a diameter of less than 2,5 micrometres

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 137  
 138

139 Personal air pollution exposure assessment

140 Each woman carried wearable devices to measure her personal exposure to NO<sub>2</sub> (passive  
141 sampler from Passam AG, Männedorf, Switzerland) and PM<sub>2.5</sub> (MicroPEM active air sampler,  
142 RTI International, Research Triangle Park, NC, USA) (Chartier et al. 2017) during 1 to 3  
143 separate weeks during pregnancy. Each woman pregnancy exposure to NO<sub>2</sub> and PM<sub>2.5</sub> was  
144 estimated by averaging the measured concentrations from the personal sensors carried by  
145 the woman. Each measurement week lasted from 4 to 10 days, with 99% of samples lasting  
146 greater than 7 days. Participants were instructed to leave devices on during the measurement  
147 week and to keep the devices close to them (within 2m) when it had to be removed (e.g.  
148 sleeping, bathing). NO<sub>2</sub> concentrations were measured by spectrophotometer using  
149 previously established methods (Hafkenscheid et al. 2009). The MicroPEM collects both real-  
150 time PM mass concentration data and a PM sample on a 25 mm PTFE filter for gold-standard  
151 gravimetric analysis (Cho et al. 2016). All filters were pre- and post-weighed at RTI  
152 International, using a microbalance (Mettler Toledo UMX2) housed in a temperature- and  
153 humidity-controlled environmental chamber (21 C, 35% RH). Real-time personal PM<sub>2.5</sub>  
154 concentrations were processed with the MicroPEM Docking Station software (RTI  
155 International, RTP, NC) at 10-s intervals and were calibrated with the corresponding  
156 gravimetric filter measurements. The instruments were calibrated once before starting each  
157 measurement with MicroPEM Docking Station software (RTI International, RTP, NC) (Cho et al.  
158 2016).

159

160

161 Lung function

162 Lung function parameters were measured in the infants (mean age 7 weeks), using an infant  
163 face mask (AMBU Size 1 Infant) during natural sleep (following regular feeding) in supine  
164 position with the head midline, following to ATS/ERS guidelines (Bates et al. 2000). The first  
165 20 to 30 breaths were removed from analysis to allow for stabilization of the infant's  
166 breathing pattern. Ten minutes of tidal breathing was then recorded, and three  
167 measurements of nitrogen multiple-breath washout (N<sub>2</sub>MBW) were performed.

168

169 *Tidal breathing*

170 The first 50 regular breaths of tidal breathing were used, excluding sighs and 10 breaths  
171 before and after a sigh. Then, mean tidal breathing parameters of flow, volumes and flow-  
172 volume loop were calculated following to the ERS/ATS guidelines (Bates et al. 2000).  
173 Outcomes were tidal volume (V<sub>T</sub>), minute ventilation (MV), respiratory rate (RR) and the time  
174 to peak tidal expiratory flow (t<sub>PTEF</sub>)/expiratory time (t<sub>E</sub>) ratio.

175

176 *Multiple-breath washout*

177 Lung volume and ventilation heterogeneity were measured by means of N<sub>2</sub>MBW technique  
178 with pure oxygen (O<sub>2</sub>), using the Exhalyzer© and Spiroware© (Ecomedics). Functional  
179 Residual Capacity (FRC) and Lung Clearance Index (LCI), the latter being defined by the  
180 number of lung volume turnovers required to reduce the concentration of N<sub>2</sub> below 2.5%,  
181 were recorded. Up to 3 satisfactory measures were obtained. All tests were carefully  
182 reviewed and accepted using the following criteria: regular breathing during quiet sleep, V<sub>T</sub>  
183 within target, no swallowing or sigh in the first 5 breaths, no sign of leak and N<sub>2</sub> concentration  
184 below 2.5 % for at least 3 consecutive breaths (end of test criteria).

185 Use of pure oxygen may induce transient hypoventilation (hV) characterized by transient  
186 decrease in tidal volume (Gustafsson et al. 2017). For each N2MBW measure, we calculated  
187 the degree of hypoventilation defined by the maximum drop of  $V_T$  in the first 15 breaths  
188 following  $O_2$  exposure as compared to the mean  $V_T$  in breaths before  $O_2$  exposure. Then, the  
189 observed LCI and FRC values were corrected for the degree of hypoventilation by using the  
190 residuals of the mixed linear regression (to account for repeated measures by subjects) of the  
191 degree of hypoventilation on LCI or FRC (Mortamais et al. 2012).

192  
193 A total of 865 valid tests were retained, with a median [Q1; Q3] of 3[2; 3] tests per child. Both  
194 for LCI and FRC, the averaged hV<sub>corrected</sub> value per subject was used.

#### 195 196 Statistical analyses

197 Separate linear regressions for each pollutant ( $NO_2$ ,  $PM_{2.5}$ ) and each lung function parameter  
198 (LCI, FRC,  $V_T$ , MV, RR,  $t_{PTEF}/t_E$ ) were used to study the associations between pre-natal  
199 exposures and newborn lung function. Regressions were adjusted for *a priori* selected  
200 confounders and predictors of newborn lung function and comprised child characteristics  
201 including age (continuous), sex, height at 2 months (continuous), gestational age at birth  
202 (continuous), season of birth (4 categories), tobacco smoking exposure (yes/no, defined as  
203 maternal active or passive smoking during pregnancy or passive exposure of the child after  
204 birth), and breastfeeding at 2 months as well as parental characteristics including parents  
205 highest educational level (< master's degree,  $\geq$  master's degree), paternal or maternal  
206 asthma, paternal or maternal rhinitis, delivery mode (vaginal delivery, c-section). To assess  
207 whether maternal exposure to air pollutants effects on newborns lung function differed  
208 between females and males, sex-stratified models and models with interaction terms were  
209 fitted. Penalized splines models using cubic regression splines with 12 knots were used to  
210 estimate the shape of the relationship between air pollutants and lung function. The optimal  
211 degree of freedom was defined by minimizing AIC and nonlinearity was evaluated with a Wald  
212 test. We relied on the following threshold for results interpretation: main effects were  
213 considered statistically significant for  $p$ -values  $\leq 0.05$ , interaction terms were considered  
214 suggestive of an interaction for  $p$ -values less than 0.20.

#### 215 216 Sensitivity analyses

217 Sensitivity analyses were conducted by excluding 1) one fourth of the newborns with the  
218 highest degree of hypoventilation ( $n=80$  for  $NO_2$  analyses and  $n=70$  for  $PM_{2.5}$  analyses) in  
219 order to minimize potential measurement error on lung function parameters, 2) women with  
220 only one measurement week of air pollutants during pregnancy to minimize potential  
221 measurement error on air pollution exposure and 3) by excluding the lowest (below 1<sup>st</sup>  
222 percentile) and highest values (above the 99<sup>th</sup> percentile) of the outcomes and exposures,  
223 resulting in the exclusion of 4% to 5% of the population of each analysis.

224  
225  
226 Analyses were carried out using SAS (version 9.4) R (version 3.6.0) software.

#### 227 228 **Results**

229  
230 Among 391 children included, 55% were males, 28% were exposed in utero or post-natally to  
231 tobacco smoking, 84% were born by vaginal delivery and 86% were still breastfed at 2



232 months (Table 1). Children were aged 49 days on average at lung function examination.  
233 Among the 391 children with at least one LCI or TBFVL measurement, 350 had LCI measured  
234 and 325 had TBFVL evaluated.  
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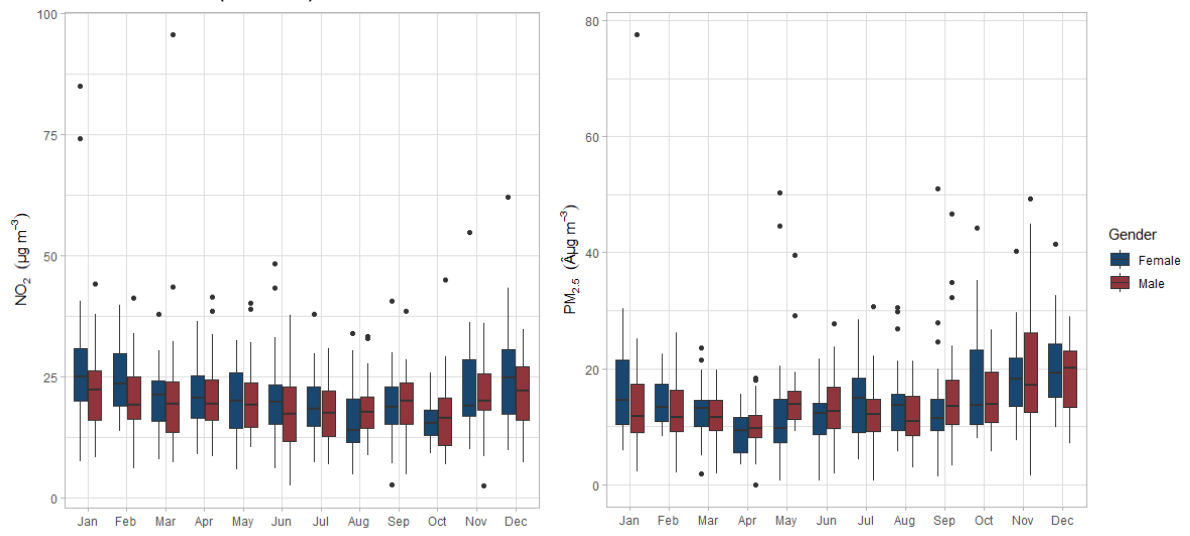
Table 1: Characteristics of the study population, SEPAGES cohort (n=391)

Characteristics	n (%)		
<b>Sex of the child</b>			
	Male	213	(54.5)
	Female	178	(45.5)
<b>Tobacco smoking exposure<sup>1</sup></b>			
	No	282	(72.3)
	Yes	108	(27.7)
<b>Season of birth</b>			
	January-March	83	(21.2)
	April-June	91	(23.3)
	July-September	111	(28.4)
	October-December	106	(27.1)
<b>Parents highest educational level</b>			
	< Master's degree	115	(29.4)
	≥ Master's degree	276	(70.6)
<b>Parental history of asthma</b>			
	No	254	(72.8)
	Yes	95	(27.2)
<b>Parental history of rhinitis</b>			
	No	135	(36.7)
	Yes	233	(63.3)
<b>Still breastfed at 2 months</b>			
	No	53	(13.8)
	Yes	332	(86.2)
<b>Delivery mode</b>			
	Vaginal	330	(84.4)
	Caesarean section	61	(15.6)
<b>Moved during pregnancy</b>			
	No	319	(81.6)
	Yes	72	(18.4)
	n	mean (std)	[min-max]
<b>Child age at exam (days)</b>	391	7.0 (1.1)	[5.4-16.1]
<b>Height at exam (cm)</b>	390	56.4 (2.2)	[50.0-63.2]
<b>Gestational age at birth (weeks)</b>	391	39.3 (1.5)	[30.0-42.0]

239 <sup>1</sup> defined as maternal active or passive smoking during pregnancy or passive exposure of the  
240 child after birth  
241  
242  
243

244 Individual measurements of personal exposure followed a seasonal trend with higher NO<sub>2</sub> and  
245 PM<sub>2.5</sub> exposure levels during the cold season (Figure 2). Average exposure to NO<sub>2</sub> and PM<sub>2.5</sub>  
246 during pregnancy was 20.2 µg/m<sup>3</sup> and 14.3 µg/m<sup>3</sup>, respectively (Table 2). Mean NO<sub>2</sub> exposure  
247 was slightly higher for women carrying female foetuses compared to women carrying males  
248 (Table 2). These average exposures were calculated, for 95.4% of women for NO<sub>2</sub> and 82% of  
249 women for PM<sub>2.5</sub>, using 2 or 3 weeks of measurements performed during pregnancy (Table  
250 S1). Only 4.9% of women for NO<sub>2</sub> and 18% for PM<sub>2.5</sub> performed only one week of  
251 measurement during pregnancy. Most of the measurement weeks were performed during  
252 the 2<sup>nd</sup> (52.1% for NO<sub>2</sub> and 44.3% for PM<sub>2.5</sub>) or 3<sup>rd</sup> (44.4% for NO<sub>2</sub> and 52.3% for PM<sub>2.5</sub>)  
253 trimesters of the pregnancy (Table S1). The distributions of average exposure to NO<sub>2</sub> and  
254 PM<sub>2.5</sub> during pregnancy were quite similar when restricting the population to women who  
255 performed 3 or ≥2 measurements weeks (Table 3).  
256  
257

258 Figure 2: Seasonal variation of measurements of NO<sub>2</sub> and PM<sub>2.5</sub> personal exposure in the  
259 SEPAGES cohort (n=391)



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264 Table 2: Personal pre-natal exposure to air pollutants and newborn lung function indicators  
 265 measured in 391 mother-child participants of the SEPAGES cohort

	All participants			Females		Males	
	n	mean (std)	[min-max]	n	mean (std)	n	mean (std)
PM <sub>2.5</sub> pregnancy (µg/m <sup>3</sup> )	338	14.3 ( 6.3)	[2.2-46.7]	158	14.2 ( 6.5)	180	14.2 ( 6.1)
NO <sub>2</sub> pregnancy (µg/m <sup>3</sup> )	391	20.2 ( 7.0)	[5.3-57.6]	178	20.8 ( 7.6)	213	19.6 ( 6.5)
LCI	350	7.6 ( 1.1)	[4.5-11.0]	158	7.3 ( 1.1)	192	7.8 ( 1.1)
FRC (ml)	350	106.4(18.1)	[62.2-89.7]	158	103.7(17.5)	192	108.6(18.3)
V <sub>T</sub> (ml)	325	34.1 ( 7.1)	[13.5-55.1]	155	32.5 ( 7.0)	170	35.6 ( 6.8)
MV (ml/kg)	325	319.1(54.3)	[155.5-509.7]	155	321.8(58.1)	170	316.7(50.5)
T <sub>PTEF</sub> /T <sub>E</sub> (%)	325	36.4 ( 9.9)	[18.8-70.7]	155	36.6 ( 9.5)	170	36.3(10.3)
RR min <sup>-1</sup>	325	46.4(11.2)	[25.4-84.6]	155	47.3(12.1)	170	45.5(10.4)

266 LCI: lung clearance index, FRC: functional residual capacity, V<sub>T</sub> :tidal volume, MV: minute  
 267 ventilation, RR: respiratory rate, tPTEF: time to peak tidal expiratory flow; tE: expiratory time

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 269  
 270

271 Table 3: Maternal NO<sub>2</sub> and PM<sub>2.5</sub> exposure levels (µg/m<sup>3</sup>) during pregnancy estimated using  
 272 personal devices, SEPAGES cohort, n=391

	n	mean	sd	Percentiles					IQR
				p5	p25	p50	p75	p95	
<b>NO<sub>2</sub> exposure</b>									
During pregnancy, for all participants	391	20.2	7.0	10.5	15.3	19.3	24.4	42.5	9.1
participants with ≥2 measurements	373	20.2	7.1	10.5	15.3	19.3	24.3	31.8	9.1
participants with 3 measurements	82	21.0	6.9	11.8	15.8	20.4	26.1	31.6	10.3
<b>PM<sub>2.5</sub> exposure</b>									
During pregnancy, for all participants	338	14.3	6.27	5.9	10.5	13.2	17.2	25.4	6.7
participants with ≥2 measurements	277	14.2	5.81	6.3	10.6	13.2	17.0	24.9	6.4
participants with 3 measurements	1	14	--	--	--	--	--	--	--

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 274  
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276 While maternal NO<sub>2</sub> exposure during pregnancy was negatively associated with all parameters  
277 of newborn's lung function (except LCI), none of these associations were statistically  
278 significant (Figure 3). Sex-specific results for NO<sub>2</sub> did not vary. A 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub>  
279 maternal personal exposure during pregnancy was associated with an adjusted 2.5 ml  
280 (representing 2.3% of the average FRC) decrease in the functional residual capacity of the  
281 newborn (p-value=0.11) (Figure 3, Table S2). This association was heterogeneous by sex  
282 subgroups with a statistically significant decrease of functional residual capacity in females (-  
283 5.2 ml (representing 5.0% of the average FRC), CI<sub>95%</sub> -9.5, -1.0, *p*=0.02), while the estimated  
284 association was close to the null for males (0.3 ml (representing 0.3% of the average FRC),  
285 CI<sub>95%</sub> -4.3, 4.8, *p*=0.91) (Figure 3, Table S2). Suggestive associations of PM<sub>2.5</sub> exposure with  
286 increased respiratory rate (2.4 min, for each 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub>, CI<sub>95%</sub> -0.7, 5.6,  
287 *p*=0.13) and decreased tidal volume (-1.6 mL, for each 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub>, CI<sub>95%</sub> -3.4,  
288 0.2, *p*=0.08) were found among females, while results were less conclusive for males (-1.2  
289 min, CI<sub>95%</sub> -3.9, 1.6, *p*=0.40 for respiratory rate and 0.1 ml, CI<sub>95%</sub> -1.7, 1.8, *p*=0.95, for tidal  
290 volume) (Figure 3, Table S2). We found evidence for effect modification by sex on the  
291 association between PM<sub>2.5</sub> and respiratory rate (p-interaction = 0.09). Other interaction terms  
292 with sex did not reach statistical significance (p-interaction>0.20) (Table S2). The penalized  
293 spline models indicated linear concentration–response relationships between both pollutants  
294 and all lung function parameters.

295

296 Sensitivity analyses

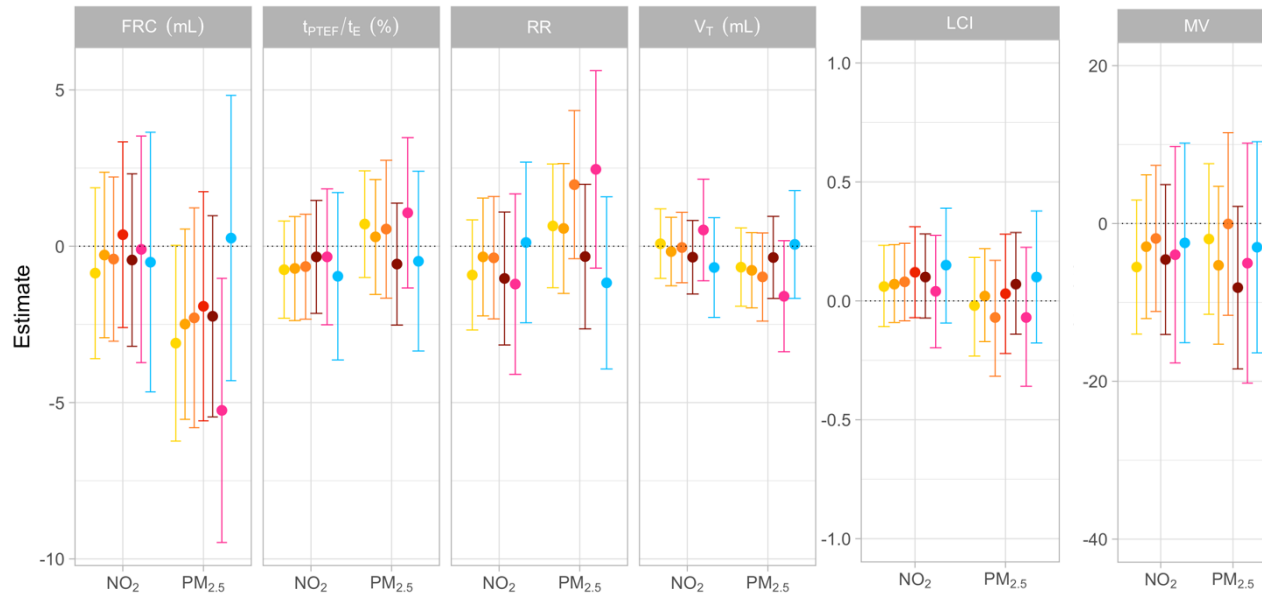
297 Results from sensitivity analyses were generally consistent albeit less significant given  
298 reduced power that resulted from excluding participants (Figure 3).

299

300

301 Figure 3: Association between maternal personal exposure to NO<sub>2</sub> and PM<sub>2.5</sub> during pregnancy (10 µg/m<sup>3</sup> increase) and lung function of the  
 302 newborn, SEPAGES cohort, n=391

- 303 ● Univariate
- Multivariate
- Participants with ≥2 measurement weeks
- Participants without extreme values
- Girls
- Boys



304 **Univariate:** regression models included air pollutant exposure. **Multivariate:** regression models were adjusted for child age (continuous), child sex, gestational age at delivery  
 305 (continuous), height at 2 months (continuous), tobacco smoking exposure (yes/no, defined as maternal active or passive smoking during pregnancy or passive exposure of the  
 306 child after birth), season of birth (4 categories), parents highest educational level (< master's degree, ≥ master's degree), paternal or maternal asthma, paternal or maternal  
 307 rhinitis, breastfeeding (no or <1 month, ≥1 month), delivery mode (vaginal delivery, c-section). **Participants with ≥2 measurement weeks:** 16 participants for NO<sub>2</sub> and 52 for  
 308 PM<sub>2.5</sub> who had only one measurement week during pregnancy were excluded from the multivariate regression models. **Participants without hypoventilation:** newborns with  
 309 the highest degree of hypoventilation were excluded from the multivariate regression models. **Participants without extreme values:** Participants with exposures or outcomes  
 310 below the 1<sup>st</sup> percentile or above the 99<sup>th</sup> were excluded from multivariate regression models (exclusion of approx. 5% of the population). **Females:** multivariate models were  
 311 restricted to females. **Males:** multivariate regression models were restricted to males.  
 312 FRC: functional residual capacity (ml), LCI: Lung clearance index, MV: minute ventilation (ml/kg),  $V_T$ : tidal volume (ml),  $T_{PTEF}/T_E$ : time to peak tidal expiratory flow/expiratory  
 313 time, RR: respiratory rate per minute.  
 314  
 315



316 **Discussion**

317 This is the first prospective study to measure personal pre-natal exposure of the mother to  
318 NO<sub>2</sub> and PM<sub>2.5</sub> and to show association with newborn lung function. Our results suggest that  
319 females, but not males, born to mothers with higher exposure to PM<sub>2.5</sub> during pregnancy  
320 were at higher risk for lower lung volumes, as reflected by the lower FRC and tidal volume  
321 measured at 2 months of age. No significant association was observed with NO<sub>2</sub>. These data  
322 add to a growing literature linking pre-natal particulate air pollution exposure to children's  
323 respiratory health (Latzin et al. 2009). They provide a key advancement in showing that such  
324 effects of PM<sub>2.5</sub> are present as early as the first 2 months of life and further suggest that  
325 females might be more sensitive to such effects.  
326

327 Comparison with studies in older children, sex differences and mechanistic insights

328 Most of the literature on effects of pre- and post-natal exposure to air pollutants on children  
329 lung function measured forced expiratory volumes after 5 years old. This evidence suggests  
330 adverse effects of pre- and post-natal PM<sub>2.5</sub> and NO<sub>2</sub> exposure on lung function level and  
331 growth (Jedrychowski et al. 2010; Korten et al. 2017; Lee et al. 2018; Milanzi et al. 2018;  
332 Schultz et al. 2018). Besides, there is growing evidence for sex-specific effects of air pollutants  
333 on respiratory health, although with mixed results regarding lung function (Bose et al. 2018;  
334 Lee et al. 2018; Leon Hsu et al. 2015; Liptzin et al. 2015; Schultz et al. 2017). Lee (Lee et al.  
335 2018) and Bose (Bose et al. 2018) investigated pre-natal ambient exposure to PM<sub>2.5</sub> and  
336 nitrate, respectively, and found increased susceptibility for lung function effects in school  
337 aged males. On the contrary, our results support potential effects of pre-natal personal PM<sub>2.5</sub>  
338 on decreased FRC and tidal volume and increased RR in females, which suggests a deficit in  
339 lung volumes in females, but not in males. Although focused on personal maternal carbon  
340 monoxide measurements as a proxy of household air pollution exposure, a study conducted  
341 on 384 newborns from rural Ghana suggest that female's lung function would be more  
342 sensitive to pre-natal household air pollution exposure than males (Lee et al. 2019). The exact  
343 mechanisms that could explain this effect in females and more generally these sex-specific  
344 effects of air pollutants on lung function remain to be fully elucidated. Differential  
345 development of the lung between males and females has been described in human and  
346 animals, indicating earlier surfactant maturation in females and smaller lungs from birth to  
347 adolescence (Carey et al. 2007; Ishak et al. 2014). A study showed that intrauterine growth  
348 restriction could particularly impact lung development in females with transient delay in post-  
349 natal alveolar formation and retinoic acid receptor expression in the lung of female rat pups  
350 (Joss-Moore et al. 2013). More generally, the developing human fetal lung transcriptome  
351 showed sex-specific differences (Kho et al. 2016) and miRNAs have been shown differentially  
352 regulated between sexes during the canalicular and sacular stages of lung development in  
353 mice (Mujahid et al. 2013). Although these elements require further investigation, they  
354 provide first insights into the biological mechanisms that may be at play.

355 Regarding PM<sub>2.5</sub>, a study showed that mice pups exposed in the pre-and post-natal period had  
356 decreased inspiratory and expiratory volumes and altered lung morphology (Mauad et al.  
357 2008). PM<sub>2.5</sub> are potent oxidant capable of generating reactive oxygen species, which can  
358 result in oxidative stress both in the mother and fetus. Fetal oxidative stress can adversely  
359 affect post-natal lung maturation, through gene expression modifications (Land and Wilson  
360 2005). Epigenetic mechanisms have also been shown sensitive to air pollutants exposure  
361 during pregnancy (Abraham et al. 2018; Gruzieva et al. 2019) and could have long term  
362 impact on the structure and function of the lung (Joss-Moore et al. 2013; Mukherjee et al.

363 2021). In this regard, early measures of newborn lung function provide a more precise  
364 understanding of the effects of in-utero exposure to air pollutants and can thus inform future  
365 studies to investigate the underlying biological mechanisms.

#### 367 Comparison with other studies in newborns

368 Very few studies have performed such early measurements of flows and volumes in healthy  
369 newborns. Performed after sedation, they are not well accepted by the parents. Without  
370 sedation, they are challenging to perform and require some time to get the child in quiet  
371 sleep, rigorous procedures and quality controls to obtain reliable data, as well as trained  
372 professionals. Yet this is crucial to investigate such effects as early changes in lung function  
373 might reflect alterations of lung development with lifetime consequences. In fact, lung  
374 function defects in infancy, through its impact on lung function peak achieved in early  
375 adulthood, may account for part of COPD in adulthood (Lange et al. 2015). Our findings that  
376 increased pre-natal PM<sub>2.5</sub> exposure in females is associated with reduced FRC and with  
377 suggestive decrease in tidal volume and increase in RR are in line with the only previous study  
378 on pre-natal air pollution effects on lung function performed in newborns (Latzin et al. 2009).  
379 This Swiss study conducted on 241 newborns showed that concentrations of PM<sub>10</sub> and NO<sub>2</sub> at  
380 ambient monitors were associated with significant increased RR and decreased tidal volume.  
381 No effects of PM were found on LCI, both in the Swiss study and in ours. Conversely, Latzin et  
382 al. found significant positive associations of PM<sub>10</sub> ambient concentrations with MV and mean  
383 tidal flows and no association with FRC, while we did show significant lower FRC in females  
384 associated with higher pre-natal personal PM<sub>2.5</sub>, but no association with MV and T<sub>PTEF</sub>/T<sub>E</sub>.  
385 Results of the South African birth cohort MACE showed some consistency with ours, with  
386 decreased FRC and tidal volume and increased RR and MV, associated with short-term  
387 exposure to PM<sub>10</sub>, while NO<sub>2</sub> related changes were less evident (Muttoo et al. 2022).

#### 389 The tradeoff between personal and outdoor air pollution exposure estimates

390 Most epidemiological studies rely on residential exposure estimates to air pollutants based on  
391 ambient exposure models as a surrogate of personal exposure. This approach does not  
392 account for exposures at other locations visited by the participant nor for indoor sources.  
393 Personal measurements allow to address these two issues, but such measurements are  
394 usually obtained for limited time periods, because of their high cost and limited acceptability  
395 for extended periods of time. Compared with outdoor estimates, personal measurements to  
396 air pollutants could increase the risk of biases from individual behaviors (Weisskopf and  
397 Webster 2017). However, in industrialized countries where people stay most of their time  
398 indoors, especially pregnant women who spend an increasing time at home towards the  
399 latter stages of pregnancy (Nethery et al. 2009), the use of personal measurements might  
400 help improving exposure characterization to air pollutants and decreasing exposure  
401 measurement error. In the Grenoble metropolitan area, a previous work conducted on  
402 pregnant women showed that PM<sub>2.5</sub> personal measurements were not correlated to the  
403 corresponding residential exposure estimates in ambient air, suggesting that personal  
404 measurements could be more representative of real exposures, in particular because it  
405 captured indoor sources (Ouidir et al. 2015). In the SEPAGES cohort, although personal  
406 measurements of air pollutants were available at different trimesters of pregnancy (mainly  
407 the 2nd and 3rd trimesters), we did not conduct trimester specific association analyses  
408 because we believe this design with a single measurement week per trimester of pregnancy is  
409 not relevant to identify critical exposure windows as it does not capture the whole trajectory

410 of air pollution exposure during pregnancy. Designs with continuous estimates of exposure  
411 throughout pregnancy are more relevant to flexibly assess critical windows of exposure  
412 (Wilson et al. 2017).

413

#### 414 Strengths and limitations

415 Beyond the two key strengths and innovations of this study, which are the repeated personal  
416 exposure measurements and the early characterization of lung function in newborns, other  
417 assets include the prospective design and the consideration of important confounders. In  
418 addition, to our knowledge, this is the first investigation of sex-specific effects of PM<sub>2.5</sub> on  
419 newborn lung function. The moderate sample size of the study might have impacted the  
420 statistical power to detect interactions. However, the stratified results suggest differential  
421 effects of PM<sub>2.5</sub> by gender, which might be driven by physiological differences in lung growth  
422 between male and female fetuses and underline the necessity to integrate child sex  
423 differences in vulnerability (Bolte et al. 2021; Liptzin et al. 2015).

424 Other potential limitations include the fact that only one to three personal measurement  
425 weeks were performed and that we did not account for post-natal exposure to PM<sub>2.5</sub>.  
426 However, in a similar study conducted on newborns, post-natal exposure to NO<sub>2</sub> and PM<sub>10</sub> did  
427 not modify the association with pre-natal exposures (Latzin et al. 2009). As for pre-natal  
428 exposure, most participants (95%) performed 2 or 3 weeks of measurements at different  
429 seasons, which were averaged over the whole pregnancy, in order to eliminate the seasonal  
430 effects. In addition, our results were robust to the exclusion of participants with only one  
431 exposure measurement. Regarding lung function tests, measurement errors in FRC and LCI  
432 parameters due to hypoventilation induced by pure oxygen during the N2MBW test may have  
433 occurred. Nevertheless, we analyzed HV-corrected FRC and LCI parameters and our results  
434 were robust to the exclusion of participants with the highest degree of hypoventilation.

435

436

#### 437 **Conclusion**

438 In summary, we studied the association of newborn lung function indicators with personal  
439 pre-natal exposure of the mother to NO<sub>2</sub> and PM<sub>2.5</sub> and pointed out that females, but not  
440 males, born to mothers with higher exposure to PM<sub>2.5</sub> during pregnancy were at higher risk of  
441 lower lung volumes. While previous literature showed that air pollution exposure alters lung  
442 development, our results provide evidence that such effects can be initiated in utero,  
443 especially in females. These early impacts of PM<sub>2.5</sub> on newborn lung function may program  
444 post-natal lung function trajectory and respiratory diseases and provide additional evidence  
445 for more stringent reductions of air pollution exposures in pregnant women and children.

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489

### 490 **Authors' contributions**

491 JL and VS designed the study. AB carried out the analyses. ES formatted figures. JL wrote the  
492 original manuscript. IP, RC provided guidance. All authors contributed to the acquisition and  
493 processing of the data. IP, AB, JQ, SLC, RC, VS revised the manuscript. All authors read and  
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495

### 496 **References**

497 Abraham E, Rousseaux S, Agier L, Giorgis-Allemand L, Tost J, Galineau J, et al. 2018. Pregnancy  
498 exposure to atmospheric pollution and meteorological conditions and placental DNA  
499 methylation. *Environ Int* 118:334–347; doi:10.1016/j.envint.2018.05.007.  
500 Bates JH, Schmalisch G, Filbrun D, Stocks J. 2000. Tidal breath analysis for infant pulmonary  
501 function testing. ERS/ATS Task Force on Standards for Infant Respiratory Function Testing.  
502 European Respiratory Society/American Thoracic Society. *Eur Respir J* 16:1180–1192;  
503 doi:10.1034/j.1399-3003.2000.16f26.x.

504 Bolte G, Jacke K, Groth K, Kraus U, Dandolo L, Fiedel L, et al. 2021. Integrating Sex/Gender into  
505 Environmental Health Research: Development of a Conceptual Framework. *Int J Environ Res*  
506 *Public Health* 18:12118; doi:10.3390/ijerph182212118.

507 Bongaerts E, Aengenheister L, Dugershaw BB, Manser P, Roeffaers MJB, Ameloot M, et al.  
508 2021. Label-free detection of uptake, accumulation, and translocation of diesel exhaust  
509 particles in ex vivo perfused human placenta. *J Nanobiotechnology* 19:144;  
510 doi:10.1186/s12951-021-00886-5.

511 Bongaerts E, Nawrot TS, Van Pee T, Ameloot M, Bové H. 2020. Translocation of (ultra)fine  
512 particles and nanoparticles across the placenta; a systematic review on the evidence of in  
513 vitro, ex vivo, and in vivo studies. *Part Fibre Toxicol* 17:56; doi:10.1186/s12989-020-00386-8.

514 Bose S, Rosa MJ, Chiu Y-HM, Hsu H-HL, Di Q, Lee A, et al. 2018. Prenatal nitrate air pollution  
515 exposure and reduced child lung function: timing and fetal sex effects. *Environ Res* 167:591–  
516 597; doi:10.1016/j.envres.2018.08.019.

517 Bougas N, Rancière F, Beydon N, Viola M, Perrot X, Gabet S, et al. 2018. Traffic-related Air  
518 Pollution, Lung Function, and Host Vulnerability. *New Insights from the PARIS Birth Cohort.*  
519 *Ann Am Thorac Soc* 15:599–607; doi:10.1513/AnnalsATS.201711-900OC.

520 Cai Y, Hansell AL, Granell R, Blangiardo M, Zottoli M, Fecht D, et al. 2020. Prenatal, Early-Life,  
521 and Childhood Exposure to Air Pollution and Lung Function: The ALSPAC Cohort. *Am J Respir*  
522 *Crit Care Med* 202:112–123; doi:10.1164/rccm.201902-0286OC.

523 Carey MA, Card JW, Voltz JW, Germolec DR, Korach KS, Zeldin DC. 2007. The impact of sex  
524 and sex hormones on lung physiology and disease: lessons from animal studies. *Am J Physiol*  
525 *Lung Cell Mol Physiol* 293:L272–278; doi:10.1152/ajplung.00174.2007.

526 Chartier R, Phillips M, Mosquin P, Elledge M, Bronstein K, Nandasena S, et al. 2017. A  
527 comparative study of human exposures to household air pollution from commonly used  
528 cookstoves in Sri Lanka. *Indoor Air* 27:147–159; doi:10.1111/ina.12281.

529 Cho S, Chartier RT, Mortimer K, Dherani M, Tafatatha T. 2016. A personal particulate matter  
530 exposure monitor to support household air pollution exposure and health studies. 2016 IEEE  
531 *Glob Humanit Technol Conf GHTC* 817–818; doi:10.1109/GHTC.2016.7857373.

532 Garcia E, Rice MB, Gold DR. 2021. Air pollution and lung function in children. *J Allergy Clin*  
533 *Immunol* 148:1–14; doi:10.1016/j.jaci.2021.05.006.

534 Gruzieva O, Xu C-J, Yousefi P, Relton C, Merid SK, Breton CV, et al. 2019. Prenatal Particulate  
535 Air Pollution and DNA Methylation in Newborns: An Epigenome-Wide Meta-Analysis. *Environ*  
536 *Health Perspect* 127:57012; doi:10.1289/EHP4522.

537 Gustafsson PM, Bengtsson L, Lindblad A, Robinson PD. 2017. The effect of inert gas choice on  
538 multiple breath washout in healthy infants: differences in lung function outcomes and  
539 breathing pattern. *J Appl Physiol Bethesda Md* 1985 123:1545–1554;  
540 doi:10.1152/jappphysiol.00524.2017.

541 Hafkenscheid TL, Fromage-Mariette A, Goelen E, Hangartner M, Pfeiffer U, Plaisance H, et al.  
542 2009. Review of the application of diffusive samplers in the European Union for the  
543 monitoring of nitrogen dioxide in ambient air. undefined.

544 He B, Huang JV, Kwok MK, Au Yeung SL, Hui LL, Li AM, et al. 2019. The association of early-life  
545 exposure to air pollution with lung function at ~17.5 years in the “Children of 1997” Hong  
546 Kong Chinese Birth Cohort. *Environ Int* 123:444–450; doi:10.1016/j.envint.2018.11.073.

547 Ishak N, Sozo F, Harding R, De Matteo R. 2014. Does lung development differ in male and  
548 female fetuses? *Exp Lung Res* 40:30–39; doi:10.3109/01902148.2013.858197.

549 Jedrychowski WA, Perera FP, Maugeri U, Mroz E, Klimaszewska-Rembiasz M, Flak E, et al.  
550 2010. Effect of prenatal exposure to fine particulate matter on ventilatory lung function of

551 preschool children of non-smoking mothers. *Paediatr Perinat Epidemiol* 24:492–501;  
552 doi:10.1111/j.1365-3016.2010.01136.x.

553 Joss-Moore L, Carroll T, Yang Y, Fitzhugh M, Metcalfe D, Oman J, et al. 2013. Intrauterine  
554 growth restriction transiently delays alveolar formation and disrupts retinoic acid receptor  
555 expression in the lung of female rat pups. *Pediatr Res* 73:612–620; doi:10.1038/pr.2013.38.

556 Kho AT, Chhabra D, Sharma S, Qiu W, Carey VJ, Gaedigk R, et al. 2016. Age, Sexual  
557 Dimorphism, and Disease Associations in the Developing Human Fetal Lung Transcriptome.  
558 *Am J Respir Cell Mol Biol* 54:814–821; doi:10.1165/rcmb.2015-0326OC.

559 Korten I, Ramsey K, Latzin P. 2017. Air pollution during pregnancy and lung development in  
560 the child. *Paediatr Respir Rev* 21:38–46; doi:10.1016/j.prrv.2016.08.008.

561 Land SC, Wilson SM. 2005. Redox regulation of lung development and perinatal lung epithelial  
562 function. *Antioxid Redox Signal* 7:92–107; doi:10.1089/ars.2005.7.92.

563 Lange P, Celli B, Agustí A, Boje Jensen G, Divo M, Faner R, et al. 2015. Lung-Function  
564 Trajectories Leading to Chronic Obstructive Pulmonary Disease. *N Engl J Med* 373:111–122;  
565 doi:10.1056/NEJMoa1411532.

566 Latzin P, Rösli M, Huss A, Kuehni CE, Frey U. 2009. Air pollution during pregnancy and lung  
567 function in newborns: a birth cohort study. *Eur Respir J* 33:594–603;  
568 doi:10.1183/09031936.00084008.

569 Lee AG, Kaali S, Quinn A, Delimini R, Burkart K, Opoku-Mensah J, et al. 2019. Prenatal  
570 Household Air Pollution Is Associated with Impaired Infant Lung Function with Sex-Specific  
571 Effects. Evidence from GRAPHS, a Cluster Randomized Cookstove Intervention Trial. *Am J*  
572 *Respir Crit Care Med* 199:738–746; doi:10.1164/rccm.201804-0694OC.

573 Lee AG, Le Grand B, Hsu H-HL, Chiu Y-HM, Brennan KJ, Bose S, et al. 2018. Prenatal fine  
574 particulate exposure associated with reduced childhood lung function and nasal epithelia  
575 GSTP1 hypermethylation: Sex-specific effects. *Respir Res* 19:76; doi:10.1186/s12931-018-  
576 0774-3.

577 Leon Hsu H-H, Mathilda Chiu Y-H, Coull BA, Kloog I, Schwartz J, Lee A, et al. 2015. Prenatal  
578 Particulate Air Pollution and Asthma Onset in Urban Children. Identifying Sensitive Windows  
579 and Sex Differences. *Am J Respir Crit Care Med* 192:1052–1059; doi:10.1164/rccm.201504-  
580 0658OC.

581 Liptzin DR, Landau LI, Taussig LM. 2015. Sex and the lung: Observations, hypotheses, and  
582 future directions. *Pediatr Pulmonol* 50:1159–1169; doi:10.1002/ppul.23178.

583 Lyon-Caen S, Siroux V, Lepeule J, Lorimier P, Hainaut P, Mossuz P, et al. 2019. Deciphering the  
584 Impact of Early-Life Exposures to Highly Variable Environmental Factors on Foetal and Child  
585 Health: Design of SEPAGES Couple-Child Cohort. *Int J Environ Res Public Health* 16;  
586 doi:10.3390/ijerph16203888.

587 Mauad T, Rivero DHRF, de Oliveira RC, Lichtenfels AJ de FC, Guimarães ET, de Andre PA, et al.  
588 2008. Chronic exposure to ambient levels of urban particles affects mouse lung development.  
589 *Am J Respir Crit Care Med* 178:721–728; doi:10.1164/rccm.200803-436OC.

590 Milanzi EB, Koppelman GH, Smit HA, Wijga AH, Oldenwening M, Vonk JM, et al. 2018. Air  
591 pollution exposure and lung function until age 16 years: the PIAMA birth cohort study. *Eur*  
592 *Respir J* 52; doi:10.1183/13993003.00218-2018.

593 Morales E, Garcia-Esteban R, de la Cruz OA, Basterrechea M, Lertxundi A, de Dicastillo MDML,  
594 et al. 2015. Intrauterine and early postnatal exposure to outdoor air pollution and lung  
595 function at preschool age. *Thorax* 70:64–73; doi:10.1136/thoraxjnl-2014-205413.

596 Mortamais M, Chevrier C, Philippat C, Petit C, Calafat AM, Ye X, et al. 2012. Correcting for the  
597 influence of sampling conditions on biomarkers of exposure to phenols and phthalates: a 2-

598 step standardization method based on regression residuals. *Environ Health Glob Access Sci*  
599 *Source* 11:29; doi:10.1186/1476-069X-11-29.

600 Mortimer K, Neugebauer R, Lurmann F, Alcorn S, Balmes J, Tager I. 2008. Air pollution and  
601 pulmonary function in asthmatic children: effects of prenatal and lifetime exposures.  
602 *Epidemiol Camb Mass* 19:550–557; discussion 561-562;  
603 doi:10.1097/EDE.0b013e31816a9dcb.

604 Mujahid S, Logvinenko T, Volpe MV, Nielsen HC. 2013. miRNA regulated pathways in late  
605 stage murine lung development. *BMC Dev Biol* 13:13; doi:10.1186/1471-213X-13-13.

606 Mukherjee N, Arathimos R, Chen S, Kheirkhah Rahimabad P, Han L, Zhang H, et al. 2021. DNA  
607 methylation at birth is associated with lung function development until age 26 years. *Eur*  
608 *Respir J* 57:2003505; doi:10.1183/13993003.03505-2020.

609 Muttoo S, Jeena PM, Rösli M, de Hoogh K, Meliefste K, Tularam H, et al. 2022. Effect of  
610 short-term exposure to ambient nitrogen dioxide and particulate matter on repeated lung  
611 function measures in infancy: A South African birth cohort. *Environ Res* 213:113645;  
612 doi:10.1016/j.envres.2022.113645.

613 Nääv Å, Erlandsson L, Isaxon C, Åsander Frostner E, Ehinger J, Sporre MK, et al. 2020. Urban  
614 PM<sub>2.5</sub> Induces Cellular Toxicity, Hormone Dysregulation, Oxidative Damage, Inflammation,  
615 and Mitochondrial Interference in the HRT8 Trophoblast Cell Line. *Front Endocrinol* 11:75;  
616 doi:10.3389/fendo.2020.00075.

617 Nethery E, Brauer M, Janssen P. 2009. Time-activity patterns of pregnant women and changes  
618 during the course of pregnancy. *J Expo Sci Environ Epidemiol* 19:317–324;  
619 doi:10.1038/jes.2008.24.

620 Ouidir M, Giorgis-Allemand L, Lyon-Caen S, Morelli X, Cracowski C, Pontet S, et al. 2015.  
621 Estimation of exposure to atmospheric pollutants during pregnancy integrating space-time  
622 activity and indoor air levels: Does it make a difference? *Environ Int* 84:161–173;  
623 doi:10.1016/j.envint.2015.07.021.

624 Pinkerton KE, Joad JP. 2006. Influence of air pollution on respiratory health during perinatal  
625 development. *Clin Exp Pharmacol Physiol* 33:269–272; doi:10.1111/j.1440-  
626 1681.2006.04357.x.

627 Schittny JC. 2017. Development of the lung. *Cell Tissue Res* 367:427–444;  
628 doi:10.1007/s00441-016-2545-0.

629 Schultz ES, Hallberg J, Andersson N, Thacher JD, Pershagen G, Bellander T, et al. 2018. Early  
630 life determinants of lung function change from childhood to adolescence. *Respir Med*  
631 139:48–54; doi:10.1016/j.rmed.2018.04.009.

632 Schultz ES, Litonjua AA, Melén E. 2017. Effects of Long-Term Exposure to Traffic-Related Air  
633 Pollution on Lung Function in Children. *Curr Allergy Asthma Rep* 17:41; doi:10.1007/s11882-  
634 017-0709-y.

635 Stern DA, Morgan WJ, Wright AL, Guerra S, Martinez FD. 2007. Poor airway function in early  
636 infancy and lung function by age 22 years: a non-selective longitudinal cohort study. *Lancet*  
637 *Lond Engl* 370:758–764; doi:10.1016/S0140-6736(07)61379-8.

638 Torday JS, Nielsen HC, Fencel M de M, Avery ME. 1981. Sex differences in fetal lung  
639 maturation. *Am Rev Respir Dis* 123:205–208; doi:10.1164/arrd.1981.123.2.205.

640 Usemann J, Decrue F, Korten I, Proietti E, Gorlanova O, Vienneau D, et al. 2019. Exposure to  
641 moderate air pollution and associations with lung function at school-age: A birth cohort study.  
642 *Environ Int* 126:682–689; doi:10.1016/j.envint.2018.12.019.

643 Weisskopf MG, Webster TF. 2017. Trade-offs of Personal Versus More Proxy Exposure  
644 Measures in Environmental Epidemiology. *Epidemiol Camb Mass* 28:635–643;

645 doi:10.1097/EDE.0000000000000686.  
646 Wilson A, Chiu Y-HM, Hsu H-HL, Wright RO, Wright RJ, Coull BA. 2017. Potential for Bias When  
647 Estimating Critical Windows for Air Pollution in Children's Health. *Am J Epidemiol* 186:1281–  
648 1289; doi:10.1093/aje/kwx184.  
649



Table S1: Design of personal exposure measurement weeks during pregnancy, SEPAGES cohort, n=391

		NO <sub>2</sub> (391 women)		PM <sub>2.5</sub> (338 women)	
		n	%	n	%
<b>Number of personal measurement</b>					
Trimester of measurement weeks					
1 measurement		18	4.6	61	18
	T1	0	0	2	3.3
	T2	10	55.5	10	16.4
	T3	8	44.4	49	80.3
2 measurements		291	74.4	276	81.7
	T2, T3	266	91.4	253	91.7
	T1, T3	20	6.9	19	6.9
	T2, T2	5	1.7	4	1.4
3 measurements		82	21.0	1	0.3
	T1, T2, T3	9	11.0	0	0
	T2, T2, T3	71	86.6	1	100
	T2, T2, T2	1	1.2	0	0
	T2, T3, T3	1	1.2	0	0

T1: trimester 1, T2: trimester 2, T3 : trimester 3 of the pregnancy

Table S2: Association between maternal personal exposure to NO<sub>2</sub> and PM<sub>2.5</sub> during pregnancy (10 µg/m<sup>3</sup> increase) and lung function of the newborn, SEPAGES cohort, n=391

Pollutant	Univariate <sup>1</sup>			Multivariate <sup>2</sup>			Participants with ≥2 measurement weeks <sup>3</sup>			Participants without hypoventilation <sup>4</sup>			Without extreme values			Females			Males			p-interaction
	n	β	p-value	n	β	p-value	n	β	p-value	n	β	p-value	n	β	p-value	n	β	p-value	n	β	p-value	
NO <sub>2</sub>																						
FRC	350	-0.86	0.53	308	-0.28	0.84	293	-0.41	0.76	228	0.37	0.81	298	-0.44	0.75	141	-0.10	0.96	167	-0.51	0.81	0.85
LCI	350	0.06	0.47	308	0.07	0.38	293	0.08	0.34	228	0.12	0.22	296	0.10	0.25	141	0.04	0.75	167	0.15	0.23	0.30
MV	325	-5.52	0.20	286	-2.94	0.53	270	-1.90	0.69				272	-4.57	0.34	134	-3.96	0.57	152	-2.46	0.70	0.76
T <sub>PTEF</sub> /T <sub>E</sub>	325	-0.75	0.34	286	-0.71	0.40	270	-0.65	0.44				275	-0.34	0.71	134	-0.34	0.76	152	-0.96	0.48	0.87
RR	325	-0.92	0.31	286	-0.34	0.72	270	-0.37	0.71				274	-1.03	0.34	134	-1.21	0.41	152	0.12	0.93	0.89
V <sub>T</sub>	325	0.08	0.88	286	-0.17	0.76	270	-0.04	0.94				272	-0.35	0.56	134	0.52	0.53	152	-0.68	0.40	0.40
PM <sub>2.5</sub>																						
FRC	<b>297</b>	<b>-3.10</b>	<b>0.05</b>	<b>265</b>	<b>-2.49</b>	<b>0.11</b>	213	-2.29	0.20	195	-1.92	0.30	255	-2.24	0.17	<b>124</b>	<b>-5.25</b>	<b>0.02</b>	141	0.26	0.91	0.26
LCI	297	-0.02	0.82	265	0.02	0.81	213	-0.07	0.55	195	0.03	0.82	254	0.07	0.50	124	-0.07	0.65	141	0.10	0.48	0.31
MV	319	-1.97	0.69	282	-5.30	0.30	238	-0.06	0.99				269	-8.13	0.12	133	-5.03	0.51	149	-3.01	0.66	0.94
T <sub>PTEF</sub> /T <sub>E</sub>	319	0.71	0.42	282	0.30	0.75	238	0.55	0.63				272	-0.57	0.56	133	1.07	0.38	149	-0.48	0.74	0.26
RR	319	0.65	0.52	282	0.57	0.59	<b>238</b>	<b>1.97</b>	<b>0.10</b>				272	-0.33	0.77	<b>133</b>	<b>2.46</b>	<b>0.13</b>	149	-1.17	0.40	<b>0.09</b>
V <sub>T</sub>	319	-0.67	0.30	282	-0.77	0.21	238	-0.98	0.17				269	0.36	0.59	<b>133</b>	<b>-1.60</b>	<b>0.08</b>	149	0.06	0.95	0.22

n=sample size, β=beta of the regression model, significant or borderline significant results are in bold. FRC: functional residual capacity (ml), LCI: Lung clearance index, MV: minute ventilation (ml/kg), V<sub>T</sub>: tidal volume (ml), T<sub>PTEF</sub>/T<sub>E</sub>: time to peak tidal expiratory flow/expiratory time, RR: respiratory rate per minute.

1: regression models included air pollutant exposure

2: regression models were adjusted for child age (continuous), child sex, gestational age at delivery (continuous), height at 2 months (continuous), tobacco smoking exposure (yes/nSo, defined as maternal active or passive smoking during pregnancy or passive exposure of the child after birth), season of birth (4 categories), parents highest educational level (< master's degree, ≥ master's degree), paternal or maternal asthma, paternal or maternal rhinitis, breastfeeding (no or <1 month, ≥1 month), delivery mode (vaginal delivery, c-section).

3: 19 participants for NO<sub>2</sub> and 68 for PM<sub>2.5</sub> who had only one measurement week during pregnancy were excluded from the multivariate regression models in order to minimize potential measurement error on air pollutants exposure.

4: newborns with the highest degree of hypoventilation were excluded from the multivariate regression models in order to minimize potential measurement error on lung function parameter