

1 **Sex ratio and reported health of the offspring of New Zealand phenoxy herbicide**  
2 **producers exposed to 2,3,7,8-Tetrachlorodibenzo-*p*-dioxin**

3

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21 **Short running title:** Dioxin exposure and offspring sex ratio

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26

27 **Abstract** (max. 250 words)

28

29 **Background.** In 1996 it was first reported that parental exposure to 2,3,7,8-  
30 Tetrachlorodibenzo-*p*-dioxin (TCDD) was associated with the birth of less boys than girls.  
31 Only a handful of studies have reported on this association since.

32 **Objectives.** To study the offspring sex ratio of men and women employed in a New Zealand  
33 phenoxy herbicide production plant between 1969 and 1984, in relation to their individual  
34 TCDD serum concentrations determined in 2007/8.

35 **Methods.** A total of 127 men and 21 women reported 355 children conceived after starting  
36 employment at the plant. The association between their TCDD serum concentrations back-  
37 calculated to the time of birth and the probability of a male birth was estimated through  
38 logistic regression, adjusting for the age of the exposed parent at birth, current body mass  
39 index and smoking.

40 **Results.** The overall sex ratio was 0.55 (197 boys, 158 girls). For fathers with serum TCDD  
41 concentrations  $\geq 20$  pg/g lipid at time of birth the sex ratio was 0.47, while 0.60 for  $< 20$  pg/g  
42 (Odds Ratio (OR) 0.49; 95% Confidence Interval (CI) 0.30-0.79). For exposed mothers the  
43 corresponding sex ratios were 0.68 and 0.53. The probability of a male birth decreased with  
44 higher paternal serum TCDD at time of birth ( $< 4$ ; 4-20; 20-100;  $\geq 100$  pg/g lipid), with ORs  
45 of 1.00 (reference); 1.00 (95% CI 0.50-2.02); 0.52 (0.29-0.92); 0.45 (0.23-0.89), p-trend:  
46 0.007.

47 **Conclusions.** This study supports earlier findings indicating that paternal serum TCDD  
48 concentrations in excess of 20 pg/g lipid are associated with a reduced sex ratio, also when  
49 exposure starts in adulthood.

50

51 **Introduction**

52 Dioxins, and in particular 2,3,7,8-Tetrachlorodibenzo-*p*-dioxin (TCDD), have been  
53 associated with a wide range of medium to long term health effects (EPA 1994). In 1996 it  
54 was first reported that fewer boys than girls were born to parents accidentally exposed to  
55 TCDD in an industrial accident in 1976 in Seveso, Italy (Mocarelli et al. 1996). Since then,  
56 this association has been examined in both animal and human studies, aiming to: (i) replicate  
57 this finding in other populations; (ii) find a mechanistic explanation; and (iii) determine the  
58 relevant dose and time window of exposure. The number of studies in humans has been  
59 limited, however, mainly due to the small number of exposed cohorts for which individual  
60 TCDD serum measurements are available.

61

62 Sex ratios are typically calculated as the number of male births divided by the total number of  
63 births. In 1998, sex ratios for children fathered by U.S. veterans of operation Ranch Hand, the  
64 unit responsible for spraying dioxin-contaminated agent orange in Vietnam from 1962 to  
65 1971 (Michalek et al. 1998), were reported. The authors did not observe a lower sex ratio  
66 related to serum TCDD concentrations at time of conception (the sex ratio of children born  
67 post service from Ranch Hand veterans with serum TCDD of <10 pg/g at time of conception  
68 was 0.51, compared to 0.51 for fathers with TCDD of  $\geq 10$  pg/g).

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70 In 2000, further findings of the Seveso study were reported (Mocarelli et al. 2000), indicating  
71 that a significantly lower sex ratio was present if fathers had been exposed to dioxin (the sex  
72 ratio of children born post-accident from unexposed fathers with serum concentrations  
73  $\leq 15$  pg/g was 0.56, compared to 0.44 for fathers with serum concentrations  $> 15$  pg/g),  
74 particularly if they were younger than 19 years at the time of exposure (sex ratio 0.38).  
75 TCDD concentrations in serum samples from mothers were not a significant predictor of the

76 probability of a male birth. This suggested that the effect was male-mediated, and particularly  
77 strong if the exposure occurred before or during puberty of the future fathers.

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79 In response to this finding, the sex ratio of the offspring of the male Austrian chloracne  
80 cohort exposed to TCDD during production of 245T in the early 1970s (n=157) was reported  
81 (Moshhammer and Neuberger 2000). The finding of a sex ratio of 0.46 for 56 children born  
82 after fathers' onset of exposure was consistent with the Seveso study, although based on  
83 small numbers.

84

85 In 2001, the sex ratio of offspring of 281 male workers from two plants producing phenoxy  
86 herbicides (including 2,4,5-T), which was part of the NIOSH study, were reported (Schnorr et  
87 al. 2001). The sex ratio among offspring, including children conceived both before and after  
88 start of employment, was not markedly associated with adult TCDD exposure at time of  
89 conception (0.51 for children from fathers with estimated <20 pg/g serum TCDD  
90 concentrations, compared to 0.56 for fathers with  $\geq 20$  pg/g serum TCDD).

91

92 In 2002, a report on Russian phenoxy herbicide producers from Ufa was published (Ryan et  
93 al. 2002), indicating a decrease in the number of boys for exposed fathers (sex ratio 0.38 for  
94 children born after the start of exposure), while no decrease was observed for exposed  
95 mothers (sex ratio 0.51 for 39 children born after start exposure), in line with the Seveso  
96 findings, although fathers were older than 20 at the time of exposure.

97

98 In summary, offspring sex ratios have now been reported for four sizable populations with  
99 known exposure to TCDD. For two (US-Ranch Hand, US-NIOSH) no association was

100 reported and for two (Italy-Seveso, Russia-Ufa), a lower sex ratio was reported to be  
101 associated with exposure in the fathers but not for the mothers.

102

103 Here we report on the sex ratio of the offspring of male and female workers employed at a  
104 phenoxy herbicide production plant in New Plymouth, New Zealand between 1969 and 1984,  
105 for whom individual TCDD serum concentration were determined in 2007/8.

106

## 107 **Methods**

108 The pesticide producers included in this study were part of the New Zealand component of  
109 the IARC international cohort of producers and sprayers of phenoxy herbicides (t Mannelje  
110 et al. 2005), and had worked for at least 1 month between 1969 and 1984 in the pesticide  
111 production plant in New Plymouth, New Zealand. Of the 1025 original production cohort  
112 members, 631 were known to be alive, living in New Zealand, and aged less than 80 years on  
113 01/01/2006. Of these 430 were randomly selected and invited to participate in a morbidity  
114 survey, and 244 completed the survey. During 2007/2008 the participants provided blood for  
115 the determination of TCDD serum concentrations of which detailed results have been  
116 reported elsewhere (t Mannelje et al. 20xx). During a face-to-face interview, completed at the  
117 time of phlebotomy, participants were asked to provide details on all their live born or still  
118 born biological children, including gender, name, date, and place of birth. The questionnaire  
119 did not ask about specific health outcomes, but a free text comments box was available for  
120 comments regarding the health of the child. Based on responses, dichotomous variables of  
121 specific health outcomes were constructed for those that were repeatedly reported.

122

123 Serum samples taken at time of interview were analyzed for concentrations of TCDD, 6 other  
124 chlorinated dibenzo-dioxins, 10 chlorinated dibenzofurans and 15 PCBs, using gas

125 chromatography-high-resolution mass spectrometry (GC-HRMS). Individual serum  
126 concentrations of TCDD at the time of phlebotomy were back-calculated to the time of the  
127 birth of the child by using a first order elimination model('t Mannetje et al. 20xx). A half-life  
128 of 7.6 years was used which was based on the results from a 15 year follow-up of U.S.  
129 Vietnam war veterans of operation Ranch Hand (Michalek and Tripathi 1999).  
130 Different exposure variables were constructed, based on (i) employment in a job that was  
131 associated with high TCDD exposure ('t Mannetje et al. 20xx) (ii) serum TCDD  
132 concentration at time of phlebotomy and (iii) estimated serum TCDD concentration at the  
133 time of birth.

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135 Sex ratios for exposure groups were calculated as the number of male births divided by the  
136 total number of births. The association between exposure and the probability of a male birth  
137 was estimated through logistic regression of correlated outcome data with children from the  
138 same parent being correlated (using SAS proc genmod with repeated statement) (2011),  
139 crude, and adjusting for the age of exposed parent at year of birth, current BMI and smoking  
140 status of the parent. The association between the natural logarithm of the estimated serum  
141 TCDD concentration at birth (ln-TCDD), and the probability of a parent- reported health  
142 problem in the offspring was estimated through logistic regression of correlated outcome  
143 data, adjusting for sex of the exposed parent, age of exposed parent at time of birth, and sex  
144 of the child.

145

146 This study received ethical approval the Central Regional Ethics Committee (ref:  
147 CEN/06/02/002) on the 19<sup>th</sup> of May 2006. All study participants provided informed consent.

148

## 149 **Results**

150 Of the 244 participants, 32 did not report having biological children. A total of 212  
151 participants reported a total of 622 births (175 fathers with 509 births, 2.9 births on average;  
152 37 mothers with 113 births, 3.1 births on average). For 10 of the 622 births, gender was not  
153 reported and these were excluded from analyses. A further 257 were excluded from the  
154 analyses because they were conceived before the parent started employment at the plant  
155 (assuming conception 0.75 year before birth), leaving 355 births for the analyses. The overall  
156 sex-ratio was 0.55. The sex ratio was lower for births in the 1970s compared to births in the  
157 1990s (table 1).

158

159 Table 2 presents the results of the logistic regressions, modelling the probability of a male  
160 birth by sex of the exposed parent. For fathers employed in a highly exposed job within the  
161 plant, a significantly different sex ratio was not observed (OR 1.11; 95%CI 0.72-1.70), nor  
162 was a longer duration in a highly exposed job associated with a significantly altered sex ratio.  
163 Only 3 children (1 girl, 3 boys) were born to mothers who worked in a highly exposed job  
164 before conception.

165

166 Having a serum TCDD concentration  $\geq 4$  picogram per gram (pg/g) lipid at the time of  
167 phlebotomy was associated with a decreased probability of a male birth for exposed fathers  
168 (OR 0.46, 95%CI 0.29-0.73), but not for exposed mothers (OR 1.40; 95%CI 0.55-2.97). For  
169 exposed fathers, there was no clear dose-response association between serum TCDD at the  
170 time of phlebotomy and the sex ratio of the offspring (table 2).

171

172 When looking at categories of estimated serum TCDD concentration at the time of birth, a  
173 dose-response association was observed for exposed fathers (p-trend=0.007). There was no  
174 decreased probability of a male birth for fathers with serum TCDD levels of 4-20 pg/g at time

175 of birth, while 20-100 pg/g TCDD at birth was associated with an OR of 0.52 (95% CI 0.29-  
176 0.92) and  $\geq 100$  pg/g with an OR of 0.45 (95% CI 0.23-0.89). For exposed mothers, the  
177 opposite pattern to that of exposed fathers was observed (i.e. higher probability of a male  
178 birth with higher maternal TCDD), but ORs were not statistically significant and based on a  
179 small number of births.

180

181 We investigated which of the variables included as confounders resulted in the largest change  
182 from the crude ORs for the association between TCDD exposure categories at the time of  
183 birth and the probability of a male birth for exposed fathers (table 3). The only variable  
184 resulting in an appreciable change of the crude OR was current BMI of the father, which  
185 itself was associated with a higher probability of a male birth. This association became  
186 statistically significant when adjusted for TCDD at the time of conception (BMI<sub><25</sub> (ref) OR=1;  
187 BMI<sub>25-30</sub> OR=1.5, 95% CI 0.9-2.7; BMI<sub>>=30</sub> OR=2.3, 95% CI 1.1-4.9).

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189 Table 4 presents the association between the father's estimated serum TCDD concentration at  
190 the time of birth and the probability of a male birth stratified by the age of first paternal  
191 exposure, assuming exposure started at the start of employment at the plant. The numbers are  
192 small, particularly for those fathers who were first exposed before the age of 30, but they are  
193 indicative of a stronger association between TCDD exposure and the probability of a male  
194 birth if first exposure occurred before the age of 37.

195

196 Additional stratifications were also performed for the association between the father's  
197 estimated serum TCDD concentration at the time of birth and the probability of a male birth,  
198 for the following variables (supplementary tables 1-4): (i) paternal age at birth; (ii) maternal  
199 age at birth; (iii) father's current BMI; (iv) year of birth of the child. These analyses indicated



200 that the negative association between TCDD and the probability of a male birth was observed  
201 independently of the age of either parent, while the association was mainly present for fathers  
202 with BMI<25 (p-trend 0.019) and for births after 1980 (p-trend <0.001).

203

204 Of the 355 births that occurred after the start of employment of the parent at the plant, a  
205 health problem was reported for 57 births (table 5). Specific health problems that were  
206 repeatedly reported included asthma, birth defects, and thyroid/gland problems. All health  
207 problems combined (any health problem reported) was not significantly associated with a  
208 serum TCDD of more than 20 pg/g at time of birth (OR 1.33; 95%CI 0.72-2.45), nor was it  
209 significantly associated with ln-TCDD (OR 1.10, 95%CI 0.91-1.32). Congenital  
210 malformations in the offspring were not more frequently reported by highly exposed parents  
211 (OR 0.54; 95%CI 0.16-1.85) and was not associated with ln-TCDD (OR 0.68, 95%CI 0.68-  
212 1.16). Asthma was reported for 9 children of exposed parents, but an OR could not be  
213 calculated due to the small numbers. None of the parents exposed to less than 20 pg/g TCDD  
214 at time of birth reported a thyroid problem in offspring born after the start of employment,  
215 whilst of the 137 children born to highly exposed parents, a thyroid problem was reported for  
216 3 (3 children of 2 fathers and 1 mother with serum TCDD at time of birth of 79, 90, and 208  
217 pg/g respectively). Although based on very small numbers, the reporting of a thyroid problem  
218 in the offspring was positively associated with ln-TCDD at time of birth (OR 1.85, 95%CI  
219 1.37-2.48).

220

## 221 **Discussion**

222 In this study, serum TCDD concentrations above 20 pg/g lipid at the time of birth for  
223 occupationally exposed fathers were associated with the birth of relatively fewer boys than  
224 girls. For occupationally exposed mothers serum TCDD concentrations were not associated

225 with a lower sex ratio, although this finding was based on much smaller numbers. These  
226 findings support a male-mediated reduction in sex ratio associated with serum TCDD  
227 concentration at the time of birth, consistent with the findings of the Seveso study (Mocarelli  
228 et al. 2000) and the Russian pesticide producers study (Ryan et al. 2002).

229

230 The sex ratio of offspring was 0.47 for fathers with serum TCDD concentrations above 20  
231 pg/g at the time of birth. This is comparable to, but not as low as, the sex ratios reported for  
232 Seveso or the Russian pesticide producers (table 6), for which TCDD exposures were  
233 generally higher than in the New Zealand producers ('t Mannetje et al. 20xx). Although this  
234 population was occupationally exposed to a variety of compounds and pesticides, we  
235 consider paternal TCDD exposure at the time of conception to be the most likely explanation  
236 for the observed association, given the consistency of our findings with those reported for the  
237 Seveso population (where the sole exposure was known to be TCDD), and the presence of a  
238 dose-response relationship for TCDD at time of birth.

239

240 The mechanism through which paternal TCDD exposure could affect the sex ratio has not yet  
241 been established, but recent animal and human studies provide some insight. In a study of  
242 TCDD-treated male mice mated with non-treated females (Ishihara et al. 2010), the Y-  
243 bearing/X-bearing sperm ratio was not significantly decreased, but the sex ratio of the 2-cell  
244 embryos of the TCDD group was significantly lower than that of the control group. In a study  
245 in rats (Ikeda et al. 2005), in utero TCDD exposure in male rats significantly decreased the  
246 number of male offspring. Another study in rats (Rowlands et al. 2006) did not observe a  
247 change in sex ratio, but no distinction between paternal and maternal TCDD exposure was  
248 made. Thus, whilst data are limited, studies in rodents are generally supportive of the  
249 hypothesis of a male-mediated reduction in sex ratio resulting from TCDD exposure starting

250 either in utero or at reproductive age. The effect is not explained by changes in the Y-  
251 bearing/X-bearing sperm ratio, nor by a disproportionate loss of male embryos of more than 2  
252 cells, and it has been proposed that a decrease in fertility of Y-bearing sperm may be  
253 responsible (Ikeda et al. 2005).

254

255 Studies of the effects of TCDD on semen in exposed human populations are limited. In the  
256 Seveso study, in utero and lactational TCDD exposure of children of exposed mothers was  
257 associated with a permanent reduction in sperm quality (lower sperm concentration, count  
258 and motility) (Mocarelli et al. 2011). This effect was also observed in rhesus monkeys (Arima  
259 et al. 2009). Seveso men exposed to TCDD in infancy also had reduced sperm concentration  
260 and motility (Mocarelli et al. 2008), while the opposite effect was seen with exposure during  
261 puberty. No effect on semen quality was seen in men exposed to TCDD as adults (Mocarelli  
262 et al. 2008). In a study of veterans of operation Ranch Hand, no associations between serum  
263 dioxin levels and testicular abnormalities, sperm count, sperm abnormalities, or testicular  
264 volume were observed (Henriksen and Michalek 1996). Thus, while there is evidence of  
265 negative effects on sperm quality when TCDD exposure occurs at young ages (in utero to  
266 puberty), there are currently no studies indicating that adult exposure to TCDD affects sperm  
267 quality.

268

269 There are several lines of evidence indicating that reduced male fertility is associated with a  
270 reduced sex ratio. For example, testicular cancer (Moller 1998), higher scrotal temperatures  
271 (Perez-Crespo et al. 2008) and older paternal age (Chahnazarian 1988), have all been  
272 associated with a reduction in the proportion of male births. While the exact mechanism  
273 remains unclear, animal studies have also linked the production of sons with fertility (Terrell  
274 et al. 2011).

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Several social conditions affecting sex ratio, possibly through a higher loss of males than females after fertilisation, have also been reported. For example, the life expectancy of a population is positively and deprivation is negatively associated with sex ratio, indicating that mothers in poor conditions are more likely to give birth to daughters (Terrell et al. 2011). There are also several reports of reduced sex ratio after earthquakes (D'Alfonso et al. 2012) and other major disasters, indicating that sudden intense maternal stress around the time of conception results in a lower sex ratio. However, these effects appear to be acute, transient, and likely female-mediated, as opposed to the long-term and male-mediated effects hypothesised for TCDD exposure.

Recent human studies indicate that the effect of male TCDD exposure on their offspring's sex ratio may not only be long-term but also dependent on the timing of male exposure in relation to age and sexual maturation. The Seveso study found that reduction in sex ratio was strongest when exposure occurred under the age of 19, indicating that the time before and during puberty may be a particularly sensitive period for dioxin reproductive toxicity in men (Mocarelli et al. 2000). In occupationally exposed cohorts such as this study and the Russian study, timing of first exposure is difficult to establish, but it is safe to assume that first employment and therefore first exposure would have occurred in adulthood (the youngest age of first employment at the plant in this study was 23). Thus, our findings, as well as those of the Russian study (Ryan et al. 2002), indicate that the effect is not limited to exposure before or during puberty, although we did observe the strongest association for fathers first exposed before the age of 37.

299 We considered a range of factors that may confound the association between TCDD and sex  
300 ratio, of which only paternal BMI was found to alter the TCDD-sex ratio association after  
301 inclusion in the model. Paternal BMI was positively associated with a male birth outcome:  
302 sex ratio of fathers with normal weight (BMI<25) was 0.47, while for overweight fathers  
303 (BMI ≥25) it was 0.60, a pattern which has been observed previously (Abu-Rmeileh et al.  
304 2011). Inclusion of current paternal BMI in the model strengthened the negative association  
305 between paternal TCDD and male birth outcome, possibly due to BMI-associated  
306 misclassification of exposure. A higher body percentage fat has been associated with slower  
307 elimination of TCDD (Michalek and Tripathi 1999), resulting in an over-estimation of  
308 historical TCDD exposure based on current TCDD determination in those with a high BMI,  
309 which may result in strengthening of the TCDD-sex ratio association when adjusting for BMI  
310 such as observed here. When stratifying the results by current paternal BMI, the strongest  
311 negative association between serum TCDD and sex-ratio was observed for the group with  
312 BMI<25, which is in line with our assumption that for this group estimated TCDD at time of  
313 birth would be less misclassified compared to the overweight group.

314

315 In this population, the overall sex ratio was higher (0.55) than expected for the general  
316 population (generally 0.51) with higher sex ratios for more recent years of birth, for which  
317 the reasons are not clear. Although sex ratio has slightly increased over time in New Zealand,  
318 in trend with increased life expectancy (Dixson et al. 2013), this cannot explain the  
319 magnitude observed here. Also, the effect is contrary to a parental age cohort effect that could  
320 be expected: the earlier births are more likely to be from younger parents and have lower  
321 birth order, which have both been associated with a higher sex ratio (Terrell et al. 2011). A  
322 paternal BMI related cohort effect would be consistent with the observed increase in sex ratio  
323 over time, given that higher paternal BMI has been associated with a higher sex ratio (Abu-

324 Rmeileh et al. 2011), but this would assume an increase in the fathers' BMI over time, on  
325 which we do not have data. Alternatively, it could in part reflect a real effect of TCDD  
326 exposure, with the highest TCDD exposure and therefore lowest sex ratio to be expected in  
327 the earlier years. Recall bias may be also involved; given that information on offspring was  
328 self-reported many years after birth, there is a possibility that recall of early losses of births,  
329 which are more common for male births, may be worse for births that occurred longer ago,  
330 resulting in a more pronounced undercount of male births for earlier years. When stratifying  
331 by year of birth, a strong dose-response association was observed for births after 1980 ( $p$ -  
332 trend $<0.001$ ), but not for births before 1980 ( $p$ -trend=0.6). This may be due to  
333 misclassification of TCDD serum concentration at time of birth, which can be expected to be  
334 more substantial for births that occurred in earlier years. In particular, when back-calculating  
335 paternal TCDD levels to the time of birth, exposure was assumed to start when employment  
336 started, which may not be the case for all participants, potentially resulting in a substantial  
337 misclassification of TCDD exposure at time of birth for those births that occurred close to the  
338 start of employment, obscuring the dose-response association for the earlier births.

339

340 We could not evaluate the effect of other potential confounders such as maternal stress, but  
341 maternal stress around conception is unlikely to be associated with paternal TCDD  
342 concentrations in this occupationally exposed population. However, stress could be a factor in  
343 some study populations where mother's stress is indirectly associated with the father's TCDD  
344 exposure, such as is the case for the Ranch Hand cohort (Michalek et al. 1998), and may be a  
345 possible explanation for the absence of an association between paternal TCDD exposure and  
346 alteration in the sex ratio in the offspring of the veterans.

347

348 In this study we did not observe that a higher serum TCDD concentration was associated with  
349 a more frequent report of health problems or congenital malformations in the offspring. Most  
350 evidence of health effects in offspring is based on studies involving in utero or perinatal  
351 TCDD exposure, with the mother as the main route of exposure. In the current study, TCDD  
352 serum concentrations were available mainly for fathers (we did not determine the mothers  
353 TCDD serum concentration of male cohort members) and the number of female cohort  
354 members was insufficient to study the association between maternal TCDD exposure and  
355 reported health outcomes in the offspring. In addition, the study used the parent's self-report  
356 of health problems in the offspring based on an open ended question, which is likely to be  
357 subject to substantial misclassification and lacks clinical verification. Notwithstanding these  
358 limitations, we did observe an association between TCDD (ln(TCDD) at time of birth) and  
359 reported thyroid problems in the offspring. Although this association is based on very small  
360 numbers, it is statistically significant and is noteworthy in the light of toxicological and  
361 mechanistic data indicating that dioxin may impair thyroid function in the offspring  
362 (Giacomini et al. 2006). Evidence in human populations is very limited, but it has been  
363 reported that children born from mothers exposed to TCDD in the Seveso incident had higher  
364 neonatal blood thyroid-stimulating hormone (b-TSH, a sensitive marker of subclinical  
365 primary hypothyroidism) than the reference population, and maternal TCDD levels estimated  
366 at the date of delivery were positively associated with neonatal b-TSH (Baccarelli et al.  
367 2008). After further testing, two children from the contaminated areas and none from the  
368 reference were diagnosed with primary hypothyroidism (Baccarelli et al. 2008). Thus, thyroid  
369 effects in the offspring associated with parental TCDD exposure may be of clinical  
370 significance and warrants further investigation.

371

## 372 **Conclusions**

373 This study lends further support to a second generation effect of TCDD exposure that started  
374 in adulthood, with paternal TCDD serum concentrations in excess of 20 pg/g lipid at time of  
375 birth associated with the birth of relatively fewer boys than girls.

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448

449 **Table 1.** Study population characteristics: number of births by plant employees conceived  
 450 after commencing employment, by parents' demographic characteristics

	fathers employed at plant (n=127)			mothers employed at plant (n=21)		
	girls (n)	boys (n)	sex ratio	girls (n)	boys (n)	sex ratio
	137	167	0.55	21	30	0.59
<i>year of birth</i>						
<1970	21	14	0.40			
70-80	54	61	0.53	5	14	0.74
80-90	42	61	0.59	13	12	0.48
>1990	20	31	0.61	3	4	0.57
<i>age parent (employed at plant) at birth</i>						
<25	19	20	0.51	3	11	0.79
25-30	47	56	0.54	7	6	0.46
30-40	59	80	0.58	9	11	0.55
≥40	12	11	0.48	2	2	0.50
<i>age other parent at birth</i>						
<25	33	44	0.57			
25-30	47	51	0.52			
30-40	30	43	0.59			
≥40	3	1	0.25			
unknown	24	28	0.54	21	30	0.59
<i>age at start employment</i>						
23-30	26	39	0.60	7	6	0.46
30-37	47	66	0.58	8	11	0.58
>37	64	62	0.49	6	13	0.68

451

452

453 **Table 2.** Association between three indicators of TCDD exposure of parent and male birth  
 454 outcome through logistic regression of correlated outcome data

	Fathers employed at plant (n=127)							Mothers employed at plant (n=21)				
	girls (n)	boys (n)	sex ratio	Crude OR	95% CI	OR <sup>1)</sup>	95% CI	girls (n)	boys (n)	sex ratio	Crude OR	95% CI
<b>Employment in highly exposed job</b>												
no	77	87	0.53	1.00	ref	1.00	ref	20	27	0.57	1.00	ref
yes	60	80	0.57	1.19	0.76-1.85	1.11	0.72-1.70	1	3	0.75	2.01	0.43-9.46
No	77	87	0.53	1.00	ref	1.00	ref	20	27	0.57		
0.1-1.5 years	20	34	0.63	1.52	0.76-3.03	1.37	0.67-2.82	1	2	0.67		
1.5-5 years	28	29	0.51	0.92	0.51-1.67	0.86	0.47-1.57	0	0	-		
≥5 years	12	17	0.59	1.27	0.76-2.11	1.33	0.81-2.16	0	1	-		
				<i>p-trend</i>	0.685		<i>p-trend</i>					0.775
<b>Serum TCDD of parent at time of phlebotomy</b>												
<4 pg/g lipid	76	114	0.60	1.00	ref	1.00	ref	14	18	0.56	1.00	ref
≥4 pg/g lipid	61	53	0.46	0.58	0.37-0.91	0.46	0.29-0.73	7	12	0.63	1.40	0.66-2.97
<4 pg/g lipid	76	114	0.60	1.00	ref	1.00	ref	14	18	0.56		
4-10 pg/g lipid	49	37	0.43	0.50	0.32-0.79	0.43	0.27-0.67	7	10	0.59		
10-25 pg/g lipid	5	9	0.64	1.27	0.38-4.23	0.90	0.29-2.79	0	1	-		
≥25 pg/g lipid	7	7	0.50	0.70	0.28-1.76	0.52	0.17-1.64	0	1	-		
				<i>p-trend</i>	0.183		<i>p-trend</i>					0.064
<b>Estimated serum TCDD of parent at time of birth</b>												
<20 pg/g lipid	74	112	0.60	1.00	ref	1.00	ref	15	17	0.53	1.00	ref
≥20 pg/g lipid	63	55	0.47	0.58	0.37-0.90	0.49	0.30-0.79	6	13	0.68	1.90	0.84-4.31
<4 pg/g lipid	59	88	0.60	1.00	ref	1.00	ref	9	9	0.50		
4-20 pg/g lipid	15	24	0.62	1.08	0.53-2.18	1.00	0.50-2.02	6	8	0.57		
20-100 pg/g lipid	30	27	0.47	0.60	0.35-1.02	0.52	0.29-0.92	6	12	0.67		
≥100 pg/g lipid	33	28	0.46	0.58	0.30-1.09	0.45	0.23-0.89	0	1	-		
				<i>p-trend</i>	0.037		<i>p-trend</i>					0.007

455 1) OR= Odds Ratio (modelling the probability of a male birth), adjusted for: age of  
 456 parent at year of birth, current BMI parent, smoking status parent

457

458 **Table 3.** Effect of adjustment for potential confounders on the association between estimated  
 459 paternal serum TCDD concentration at time of birth and the probability of a male offspring.

TCDD' ) (pg/g)	gir ls	bo ys	crude		father's current BMI		smoking		age father at birth		age mother at birth		year birth child	
			OR	95%CI	OR	95%CI	OR	95%CI	OR	95%CI	OR	95%CI	OR	95%CI
<4	59	88	1.0	ref	1.0	ref	1.0	ref	1.0	ref	1.0	ref	1.0	ref
4-20	15	24	1.1	0.5-2.2	1.0	0.5-2.0	1.1	0.5-2.2	1.1	0.5-2.2	1.1	0.6-2.3	1.1	0.5-2.5
20-100	30	27	0.6	0.4-1.0	0.5	0.3-0.9	0.6	0.4-1.0	0.6	0.3-1.0	0.6	0.4-1.0	0.6	0.3-1.0
≥100	33	28	0.6	0.3-1.1	0.5	0.2-0.9	0.6	0.3-1.1	0.6	0.3-1.1	0.6	0.3-1.1	0.7	0.4-1.4
ORs associated with categories (see footnote) of the potential confounders: (adjusted for paternal TCDD at birth)					1.0	(BMI<25)	1.0	(never)	1.0	(age<25)	1.0	(age<25)	1.0	(<1970)
					1.5	0.9-2.7	1.1	0.7-1.8	1.2	0.6-2.5	0.8	0.4-1.4	1.9	0.8-4.2
					2.3	1.1-4.9	1.1	0.5-2.4	1.2	0.6-2.5	0.9	0.5-1.7	2.2	0.9-5.1
									0.8	0.3-2.2	0.2	0.0-2.0	2.0	0.8-5.1

460

461 1) serum TCDD of father at time of birth

462 OR: crude Odds Ratio

463 OR1 adjusted for BMI: 4 categories: <25; 25-30; ≥30; missing (for missing BMI the OR is  
 464 not reported)

465 OR2 adjusted for Smoking: 3 categories: never; ex; current

466 OR3 adjusted for Age father at birth: 4 categories: <25; 25-30; 30-40; ≥40

467 OR4 adjusted for Age mother at birth: 5 categories: <25; 25-30; 30-40; ≥40; missing (for  
 468 missing mother's age at birth the OR is not reported)

469 OR5 adjusted for the year of birth of the child: 4 categories: <1970, 1970-80, 1980-90, >1990

470

471 **Table 4.** Association between estimated paternal serum TCDD concentration at time of birth  
 472 and the probability of a male offspring, by father's age of first exposure.

<i>fathers employed at plant (n=127)</i>							
<b>age father at start employment</b>	<b>girls (n)</b>	<b>boys (n)</b>	<b>sex ratio</b>	<b>Crude OR</b>	<b>95% confidence interval</b>	<b>OR<sup>1)</sup></b>	<b>95% confidence interval</b>
<b>23-30</b>							
<4 pg/g lipid	15	24	0.62	<b>1.00</b>	ref	<b>1.00</b>	ref
4-20 pg/g lipid	4	9	0.69	<b>1.37</b>	0.36-5.31	<b>2.00</b>	0.35-11.4
20-100 pg/g lipid	4	5	0.56	<b>0.51</b>	0.16-1.68	<b>0.17</b>	0.04-0.68
≥100 pg/g lipid	3	1	0.25	<b>0.20</b>	0.03-1.37	<b>0.04</b>	0.01-0.26
				<i>p-trend</i>	<i>0.128</i>	<i>p-trend</i>	<i>0.016</i>
<b>30-37</b>							
<4 pg/g lipid	24	43	0.64	<b>1.00</b>	ref	<b>1.00</b>	ref
4-20 pg/g lipid	3	5	0.63	<b>0.94</b>	0.19-4.75	<b>1.26</b>	0.20-8.08
20-100 pg/g lipid	12	11	0.48	<b>0.51</b>	0.25-1.07	<b>0.37</b>	0.16-0.85
≥100 pg/g lipid	8	7	0.47	<b>0.49</b>	0.12-2.09	<b>0.59</b>	0.18-1.95
				<i>p-trend</i>	<i>0.148</i>	<i>p-trend</i>	<i>0.062</i>
<b>&gt;37</b>							
<4 pg/g lipid	20	21	0.51	<b>1.00</b>	ref	<b>1.00</b>	ref
4-20 pg/g lipid	8	10	0.56	<b>1.20</b>	0.42-3.48	<b>2.02</b>	0.78-5.21
20-100 pg/g lipid	14	11	0.44	<b>0.75</b>	0.28-2.05	<b>0.87</b>	0.34-2.25
≥100 pg/g lipid	22	20	0.48	<b>0.86</b>	0.35-2.12	<b>1.22</b>	0.48-3.13
				<i>p-trend</i>	<i>0.625</i>	<i>p-trend</i>	<i>0.934</i>

473  
 474 1) OR= Odds Ratio (modelling the probability of a male birth), adjusted for: age of parent at  
 475 year of birth, current BMI parent, smoking status parent

476



477 **Table 5.** Association between an estimated parental  $\geq 20$  pg/g TCDD serum concentration at  
 478 time of birth and the probability of a parent-reported health problem in the offspring.

<i>355 births after start employment</i>								
	TCDD <20 (218)		TCDD $\geq 20$ (137)		OR <sup>1)</sup>	95% confidence interval	OR for ln(TCDD) continuous	95% confidence interval
any health problem reported	33	15%	24	18%	1.33	(0.72-2.45)	1.10	(0.91-1.32)
congenital malformation	13	6%	5	4%	0.54	(0.16-1.85)	0.89	(0.68-1.16)
thyroid problem <sup>2)</sup>	0	0%	3	2%	-	-	1.85	(1.37-2.48)

479

480 1) OR= Odds Ratio, adjusted for: age of parent at year of birth, sex of exposed parent, sex of  
 481 child

482 2) For none of the offspring with reported thyroid problem, the parent reported a thyroid  
 483 problem. Of the 3 children reported to have thyroid problems, 2 were from an exposed father  
 484 and 1 from an exposed mother. The OR could not be adjusted for age of exposed parent at  
 485 year of birth.

486

487 **Table 6.** Sex ratios reported for the offspring of TCDD exposed populations.

	<i>Non-exposed group</i>		<i>TCDD exposed group</i>		Sex ratio
	Children (n)	Sex ratio	Paternal TCDD at the time of conception	Children (n)	
US, Ranch Hand (Michalek et al. 1998)	346	0.51	≥10 pg/g	557	0.51
Italy, Seveso (Mocarelli et al. 2000)	271	0.56	>15 pg/g	403	0.44
US, NIOSH (Schnorr et al. 2001)	292	0.51	≥20 pg/g	252	0.56
Russia, Ufa (Ryan et al. 2002)	Ufa city	0.51	not reported	188	0.38
New Zealand (this study)	186	0.60	≥20 pg/g	118	0.47

488