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| Title | Concentrations of perfluoroalkyl substances in human milk from Ireland: Implications for adult and nursing infant exposure |
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| Publication Date | 2019-12-20 |
| Publisher | Elsevier |

Concentrations of Perfluoroalkyl substances in human milk from Ireland: Implications for adult and nursing infant exposure

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16 **Abstract**

17 Concentrations of 10 perfluoroalkyl substances (PFASs) were measured in 16 pools of human
18 milk from Ireland. Only four PFASs were detected (PFOA, PFNA, PFHxS and PFOS), with
19 concentrations dominated by PFOA which was detected in all samples at a median of 0.10
20 ng/mL. Concentrations and the relative abundance of PFASs in Ireland are within the range
21 reported for other countries. Estimated exposures for nursing infants to perfluorooctanoic
22 acid (PFOA) and perfluorooctane sulfonate (PFOS) do not suggest a health concern. A one
23 compartment pharmacokinetic model was used to predict the intakes of PFOS and PFOA
24 required to support the observed concentrations in human milk. This suggests current adult
25 exposure in Ireland to PFOS is below the provisional tolerable weekly intake (TWI) proposed
26 by EFSA. In contrast, the model predicts that the maximum concentration detected in human
27 milk in this study, implies a level of adult exposure that would exceed EFSA's provisional
28 TWI for PFOA. As exposure of the Irish population to PFASs via drinking water, indoor air
29 and dust is well-characterised, current understanding suggests that the major contributor to
30 overall exposure of the Irish population is via the diet and/or less well-studied pathways like
31 dermal uptake from PFAS-containing fabrics and cosmetics.

32 **Highlights**

- 33 • PFOA, PFOS, PFNA, and PFHxS detected in Irish human milk
- 34 • Concentrations within the range of studies elsewhere
- 35 • Exposures of nursing infants to PFOS and PFOA not of health concern
- 36 • Modelled adult intakes of PFOA in some instances exceed provisional EFSA TWI
- 37 • Measurement of Irish exposure via the diet and dermal uptake recommended

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| 38 | Keywords |
| 39 | Human biomonitoring |
| 40 | PFASs |
| 41 | PK modelling |
| 42 | PFOS |
| 43 | PFOA |

44 **Introduction**

45 Perfluoroalkylated substances (PFAS) is a collective term for a large group of fluorinated
46 compounds, including perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA).
47 PFOS and PFOA were widely used for stain proofing and water resistant coatings for fabrics
48 and carpets, paper products (including food grade products), and firefighting foams (Buck et
49 al, 2011). Although imparting beneficial longevity in the context of their commercial
50 application, the strength of the C-F bond renders PFASs resistant to thermal, chemical and
51 biological degradation and capable of bioaccumulation and long-range environmental
52 transport, exemplified by their detection in the Arctic (Chaemfa et al, 2010; Sonne, 2010;
53 Zhao et al, 2012). Coupled with toxicological concerns (Lindstrom et al, 2011), such
54 properties have resulted in PFOS and its salts, as well as perfluorooctane sulfonyl fluoride
55 (POSF) being listed as persistent organic pollutants (POPs) under the United Nations
56 Environment Programme's Stockholm Convention in 2009 (Stockholm Convention, 2009).
57 Currently, PFOA is recommended for listing under this Convention, while the C₆ analogue of
58 PFOS - perfluorohexane sulfonate (PFHxS) - is under review for listing, and a potential
59 proposal exists at the EU level to consider for listing, C₁₀-C₁₄ analogues of PFOA (including
60 perfluorononanoic acid (PFNA) and its salts. Moreover, the European Union has identified
61 PFOA, PFNA, and PFHxS as substances of very high concern (ECHA, 2019), while the
62 European Food Safety Authority (EFSA) has promulgated provisional tolerable weekly
63 intake (TWI) values for PFOS and PFOA of 13 ng/kg bw/week and 6 ng/kg bw/week
64 respectively (EFSA, 2018). Furthermore, EFSA is currently evaluating the evidence for
65 human health effects arising from exposure to a range of other PFASs.
66 Current understanding of the pathways of human exposure to PFASs is that whilst diet
67 constitutes the principal pathway for most individuals, indoor air and dust play minor but
68 potentially significant roles (Harrad et al, 2010), with drinking water representing a

69 potentially important additional source of exposure to PFASs (Jian et al, 2017). As part of the
70 ELEVATE project funded by the Environmental Protection Agency of Ireland, we recently
71 reported concentrations of brominated flame retardants (BFRs), PFOS, PFOA, PFHxS,
72 PFNA, and other PFASs in drinking water, and in indoor air and dust from cars, homes,
73 offices and school classrooms in the Republic of Ireland (Harrad et al, 2019b; Wemken et al,
74 2019). *Inter alia*, by multiplying our data on concentrations of PFASs by exposure factors
75 (e.g. daily air inhalation rates etc), we evaluated the relative contribution of these different
76 exposure pathways of PFASs. An alternative approach to elucidating the relative significance
77 of different exposure pathways is the application of simple pharmacokinetic (PK) models.
78 Such models have been used to predict the body burdens of PFOS and PFOA in Australians
79 based on intake data from different exposure pathways (Thompson et al, 2010). Comparison
80 of these predicted body burdens with observed body burdens for the population in question
81 highlight discrepancies between predicted and observed body burdens and facilitate
82 identifications of gaps in understanding that might account for such discrepancies. Moreover,
83 they may also be employed to derive estimates of exposure via a specific pathway about
84 which data are lacking, provided that body burdens are known, and other exposure pathways
85 are well-characterised.

86 While a previous study measured concentrations of PFOS and PFOA in human milk samples
87 collected in 2010 from Ireland (Pratt et al, 2013); the detection limits of this study were quite
88 high – i.e. 0.5 ng/mL and 1.0 ng/mL for PFOS and PFOA respectively in human milk. As a
89 consequence, neither PFOS nor PFOA were detected in any of the 11 pooled samples
90 analysed, thereby limiting the application of these data in a PK model. In the current study,
91 we therefore collected samples of human milk from 92 Irish primiparas, and pooled these to
92 provide 16 samples which were analysed for concentrations of PFASs. It is important to note
93 that the previous study of human milk in Ireland also provided data on concentrations of

94 brominated flame retardants (BFRs) in pooled samples (Pratt et al., 2013). Comparability of
95 the design of the current study with this previous study was thus necessary to facilitate
96 elucidation of temporal trends in BFR concentrations in human milk in Ireland (Wemken et
97 al, 2020). Hence, while analysis of individual human milk samples can reveal different
98 information to analysis of pooled samples, coupled with the fact that the PK model of
99 Thompson et al (2010) used estimates of PFAS body burdens derived from measurements in
100 blood serum (as the most widely used human biomarker of PFAS exposure); we adapt this
101 PK model to make use of our concentrations in human milk. Specifically, given that no
102 estimates exist of the dietary exposure of the Irish population, we apply the model here in
103 conjunction with our data on human milk and our previously-reported estimates of non-
104 dietary exposure. In this way, we predict the level of exposure required to support our
105 observed human milk concentrations and by subtracting non-dietary exposure, derive
106 estimates of the maximum level of dietary exposure. Moreover, given the elevated detection
107 limits achieved in the previous study of PFASs in Irish human milk, our study constitutes in
108 effect the first such data for Ireland, and the concentrations detected are compared with those
109 in previous studies in other countries to place Irish data in an international context. Our data
110 on PFASs in human milk are also interpreted to provide insights into the exposure of nursing
111 infants to PFASs in Ireland.

112

113 **MATERIALS AND METHODS**

114 **Human milk sample collection**

115 With slight deviations, human milk sampling and donor recruitment in this study was
116 conducted in accordance with the 4th WHO UNEP guidelines for developing a survey of
117 human milk for persistent organic pollutants (WHO (World Health Organisation), 2007) and
118 was consistent with procedures followed in a previous study of PFASs and BFRs in Irish

119 human milk (Pratt et al., 2013). Study protocols and design were approved by the Clinical
120 Research Ethics Committee of the Galway University Hospital (Ref: C.A. 1578) and the
121 Research Ethics Committee of the Coombe Womens and Infants University Hospital in
122 Dublin (No. 30-2016).

123 Breast milk samples were collected between 3 to 8 weeks postpartum from primiparas who
124 were in good health and exclusively feeding one infant. Participants were required to have
125 resided at their present address for a minimum of five years before sample collection. While
126 WHO Guidance stipulates that participants should be not older than 30 years; in Ireland, 65%
127 of primiparas are aged 30 – 40 years old (Central Statistics Office, 2018), and thus
128 recruitment selection criteria were amended allow recruitment of mothers up to and including
129 40 years of age. This was consistent with the previous Irish study that included mothers up to
130 and including 41 years old (Pratt et al., 2013). Eligible participants signed a consent form and
131 filled out a questionnaire to provide contextual information.

132

133 Mothers were recruited when attending breast feeding clinics at the same two Irish maternity
134 hospitals from which mothers were recruited in the study of Pratt et al (2013), namely
135 University Hospital Galway (UHG) and the Coombe Womens and Infants University
136 Hospital (Coombe), Dublin. Breast milk samples of between 30 and 60 mL were collected
137 from each participant in clean polypropylene bottles and stored at – 18 °C until analysis.

138 In total, 92 breast milk samples were collected (UHG n=59; Coombe n=33). Samples were
139 thawed at room temperature and vortexed to homogenise before pooling in equal parts by
140 volume. Contextual data provided by the mothers in response to the study questionnaire (see
141 Supplementary Data) were used to inform the creation of sixteen sample pools depending on
142 their place of birth (Ireland, UK, EU, or non-EU), place of residence for the last five years
143 (urban or rural) with two pools created that comprised samples from mothers indicating that

144 they consumed fish at least twice a week (fish-consumer pools). Each pool contained aliquots
145 of 30 mL of milk from each individual constituent sample (15 mL for the fish-consumer
146 pools as there was less milk available from the individual donors to these pools), with the
147 number of individual samples per pool ranging between 3 and 10. Following pooling, milk
148 was freeze dried at -50 °C for 72 hours (using a Christ beta 1-8 LSC plus freeze drier) to
149 prepare for analysis.

150 **Sample preparation and analysis**

151 **Extraction & Clean-up**

152 Extraction of breast milk samples was performed based on methods previously published by
153 Kärman et al. (2006). For consistency with our measurements of PFASs in Irish drinking
154 water, indoor air and dust (Harrad et al, 2019b); in addition to PFOS, PFOA, PFNA, and
155 PFHxS, we measured the following other PFASs: perfluorobutane sulfonate (PFBS),
156 perfluorooctane sulfonamide (FOSA), its methyl and ethyl derivatives (MeFOSA and
157 EtFOSA), as well as methyl and ethyl perfluorooctane sulfonamido ethanols (MeFOSE and
158 EtFOSE). Five mL of breast milk were added to a centrifuge tube and spiked with 20 µL of
159 an internal standard solution (containing 1 ng/µL of M8PFOS, M8PFOA, M8FOSA,
160 MPFHxS, MPFNA, d-N-MeFOSA, d-N-EtFOSA in methanol). Five mL of formic acid (50%
161 in H₂O) was added and the sample was vortexed for 2 minutes. The entire mixture was
162 transferred on to an Oasis WAX (6 mL/150 mg, Waters) solid phase extraction (SPE)
163 cartridge, preconditioned with 6 mL MeOH (0.1% NH₄OH) and 6 mL MilliQ water. After
164 allowing samples to load at 1 drop/second, cartridges were rinsed with 6 mL of 25 mM
165 sodium acetate buffer (pH 4) and 6 mL of H₂O, before drying under vacuum for 10 minutes.
166 Target analytes were eluted with 6 mL of MeOH (0.1% NH₄OH). Extracts were concentrated
167 to 1 mL and passed through a 0.2 µm syringe filter before further concentration to 100 µL in
168 methanol and transfer to autosampler vials ready for analysis.

169

170 **Instrumental Analysis**

171 PFASs were analysed on a Sciex Exion HPLC coupled to a Sciex 5600+ triple TOF MS. A
172 full description of the instrumental methodology is reported elsewhere (Harrad et al. 2019a).
173 Briefly, 10 μ L of extract were injected onto a Raptor C18 column (1.8 μ m particle size, 50
174 mm length, 2.1 mm internal diameter, Restek). At a flow rate of 0.4 mL/minute a mobile
175 phase gradient was ramped from 80 % Mobile Phase A (5 mM ammonium formate in water),
176 20% mobile phase B (5 mM ammonium formate in MeOH) to 95 % mobile phase B over 6
177 minutes. This was held for 0.5 minutes before equilibrating back to 20 % mobile phase B for
178 1.5 minutes. The triple TOFMS was operated in MS/MS mode equipped with a Turbo V
179 source which was operated in negative mode using electrospray ionisation at a voltage of -
180 4,500 V. The curtain gas was set at 25 psi, whilst the nebulizer gas (source gas 1) was set at
181 25 psi and the drying gas (source gas 2) at 35 psi. The CAD gas was set to medium and
182 temperature was 450 °C. The MS data was acquired using automatic information dependent
183 acquisition (IDA) with two experiment types: (i) survey scan, which provided TOF-MS data;
184 and (ii) dependent product ion scan using a collision energy of -40V and a collision a spread
185 of 30 V. Quantification of individual PFAS was performed in Multiquant 2.0 using the
186 MS/MS transitions and retention times reported in Table SD-1 for identification.

187

188 **Quality Assurance/Quality Control**

189 A reagent blank was analysed with every batch of samples. None of the target compounds
190 were detected in blank samples at concentrations above 5 % of any of the sample
191 concentrations. Therefore, results were not corrected for blank residues and method limits of
192 quantification (LOQ) were estimated based on S/N = 10:1. Average LOQs ranged from 0.01
193 to 0.1 ng/mL for PFAS (Table SD-2). In the absence of a certified reference material,

194 replicate 5 mL aliquots (n=5) of bovine milk were spiked with 5 ng of target analytes. All
195 analyses produced an average recovery of target analytes of 80-120 % with a relative
196 standard deviation of $\leq 15\%$ as detailed in Table SD-3.

197

198 **Estimation of the intake of PFASs by nursing infants in Ireland**

199 To estimate the intake of PFASs by 1 month old nursing infants consuming human milk in
200 this study we used Equation 1:

$$201 \quad D_i = \frac{C_{PFAS} \times DV_{breast\ milk}}{BW} = ng\ kg^{-1}\ bw\ day^{-1} \text{ (equation 1)}$$

202 Where D_i is the estimated daily intake normalised to body weight (ng/kg bw/day); C_{PFAS} is
203 the concentration of a given PFAS in human milk (ng/mL); $DV_{breast\ milk}$ is the daily volume of
204 breast milk consumed (mL/day) and BW represents the body weight (kg). For both these
205 parameters, U.S. EPA guidelines (USEPA, 2002) were used, specifically, an average intake
206 of 702 mL milk per day for a 1 month old infant weighing 4.14 kg.

207 **First order Pharmacokinetic (PK) model for PFASs**

208 A simple, one-compartment, first order pharmacokinetic (PK) model based upon that
209 reported by Thompson et al (2010) was used to investigate the relationship between predicted
210 exposure intakes via various pathways and concentrations in human breast milk. In this
211 instance, we apply the model to predict the level of exposure that would be required to
212 support the measured concentrations in human milk.

213 The model is expressed as equation 2:

$$214 \quad \frac{d(CP)}{dt} = \left(\frac{DI(t)}{Vd} - kP \times CP(t) \right) \text{ (equation 2)}$$

215 Where CP is the concentration (ng/mL) of the target PFASs in serum; Vd is the volume of
216 distribution (mL serum/kg bw), DI is the daily absorbed intake (ng/kg bw/day) = daily intake
217 multiplied by the absorption efficiency, and kP is the first order elimination rate from the

218 body (day^{-1}). This equation can be rearranged, assuming steady state conditions, to yield
219 equation 3:

$$220 \quad DI = CP \times kP \times Vd \text{ (equation 3)}$$

221 The volume of distribution is defined as the amount of a substance in the body divided by its
222 concentration in the serum or blood ($Vd \text{ [mL/kg bw]} = \text{mass in body [ng/kg bw]} /$
223 $\text{concentration in serum or blood [ng/mL]}$). The values used here are those reported by
224 Thompson et al (2010), namely 230 and 170 mL/kg bw for PFOS and PFOA respectively.
225 The elimination rate constant $kP = \ln 2 / t_{1/2}$, with the values used here being 0.000352 and
226 0.000826 day^{-1} for PFOS (Bartell et al (2010) and PFOA (Olsen et al, 2007) respectively.
227 While an absorption efficiency of 91% was assumed for both PFOS and PFOA by Thompson
228 et al (2010); other studies (Alves et al. 2017; Li et al, 2015) have reported lower values of 11-
229 99% for PFOA - with most solid foods below 70% - and $62 \pm 5.6\%$ for PFOS in fish. On this
230 basis, we apply here an intermediate absorption efficiency value of 81%. Additionally,
231 partition coefficients between serum samples and breast milk samples were used to estimate
232 PFAS concentrations in serum equivalent to their measured concentrations in breast milk.
233 Specifically, we assumed that breast milk concentrations were 1.5% and 3.8% of those in
234 serum for PFOS (EFSA, 2018) and PFOA (Haug et al, 2011) respectively.

235

236 **Statistical analysis**

237 Statistical analysis was performed using Excel for Mac version 16.27. For the purposes of
238 statistical analysis, where the concentration of a given PFAS in a sample was <LOQ, the
239 concentration was assumed to equal the fractional detection frequency \times LOQ.

240

241 **RESULTS & DISCUSSION**

242 **Concentrations and relative abundance of PFASs in human milk from Ireland**

243 A summary of concentrations and detection frequencies (DFs) for those target PFASs
244 detected in at least one pooled human milk sample in this study are presented in Table 1 (the
245 full data set is presented in Table SD-4). Concentrations of the other PFASs targeted, i.e.
246 FOSA, EtFOSA, MeFOSA, EtFOSE, MeFOSE and PFBS were all below detection limits (<
247 0.05-0.1 ng/mL) in every pooled sample and are thus not discussed further. Of those PFASs
248 that were detected, PFOA was present in all samples, followed by PFNA (69%), PFOS (62%)
249 and PFHxS (31%). Consistent with possessing the highest detection frequency, PFOA was
250 the PFAS present at the highest concentration in this study (0.016 – 0.344 ng/mL, median
251 0.10 ng/mL). Table 1 compares our data with those from selected other studies. Such
252 comparison reveals both the relative abundance and absolute concentrations in Irish human
253 milk to fall within the range reported previously elsewhere in the world. In terms of temporal
254 trends, while no PFAS were detected in the previous Irish human milk survey which analysed
255 pooled samples collected in 2011 (Pratt et al, 2013), the detection limits in this previous study
256 exceeded even the maximum concentrations reported here and thus no meaningful temporal
257 trend can be elucidated for Ireland. We also inspected our questionnaire data on possible
258 factors that might influence PFAS concentrations in our samples for possible explanations for
259 the observed variation in PFAS concentrations between different pooled samples. However,
260 no such relationships were evident – e.g. no obvious differences were observed between
261 those comprising donors from rural as opposed to urban locations.

262

263 **Nursing infants' intake of PFASs via breast milk**

264 Table 2 provides estimated intakes of our target PFASs based on a 1 month old infant
265 weighing 4.14 kg and consuming 702 mL/day of breast milk containing PFASs at the median
266 and 95th percentile concentrations reported in this study. As noted earlier, EFSA have
267 proposed provisional tolerable weekly intake (TWI) values for PFOS and PFOA of 13 and 6

268 ng/kg bw/week respectively (EFSA, 2018). However, direct comparisons between our
269 estimates of exposure of 1 month old nursing infants to PFOS and PFOA and these
270 provisional TWI values are problematic. This is because the TWIs are derived on the basis of
271 steady state concentrations in blood serum and for PFOA a toxicological end point of
272 increased serum cholesterol *in adults*. For PFOS, the critical toxicological end point
273 identified by EFSA was decreased antibody response post vaccination in children. With
274 respect to this, EFSA pinpointed the serum concentration in 5 year old children above which
275 the risk of this adverse effect was of concern, to be 10.5 ng/mL. Reassuringly, the human
276 milk concentrations reported here do not indicate a health concern based on comparison with
277 the concentrations used in modelled breast feeding scenarios carried out by EFSA.
278 Specifically, even consumption over 6 months of the maximum concentration of PFOS in
279 human milk in this study (0.12 ng/mL) was predicted to result in a serum concentration below
280 10.5 ng/mL (EFSA, 2018). Notwithstanding this reassuring assessment, further measures to
281 reduce the exposure of the Irish population to PFASs are recommended to reduce
282 concentrations of these contaminants in human milk.

283

284 **Modelling of daily intakes of PFOS and PFOA required to support observed human** 285 **body burdens in Ireland**

286 Equation 3 was used to derive values of daily absorbed intake (DI) that would be required to
287 support our observed concentrations of PFOS and PFOA in human milk. These represent the
288 sum of exposures from all pathways. From these DI values we subtracted our recently
289 reported daily intakes for the Irish population via inhalation of indoor air, ingestion of indoor
290 dust, and consumption of drinking water (Harrad et al., 2019b). Table 3 shows the results of
291 this modelling exercise and demonstrates that for PFOS, even based on the maximum
292 concentrations in human milk in this study, the additional exposure required to support such a

293 body burden is - at 728 pg/kg bw/day - below the provisional EFSA TWI value that is
294 equivalent to 1857 pg/kg bw/day. The situation is less reassuring for PFOA. As shown in
295 Table 3, while average and median body burdens do not suggest additional exposures of
296 concern; the maximum PFOA concentration in human milk in this study, suggests additional
297 exposure of 1478 pg/kg bw/day, which is approximately twice EFSA's provisional TWI for
298 PFOA. It is important to stress at this point the uncertainties inherent in the PK model
299 employed here. Specifically, while we consider here only recent exposures via air, dust, and
300 drinking water; given the long human half-lives of PFOS and PFOA, and likely temporal
301 changes in their concentrations in the environment, the body burdens indicated by
302 concentrations in human milk will reflect a complex integral of both recent and past
303 exposures. Moreover, more research is required to enhance our knowledge of the human half-
304 lives, absorption efficiencies, and partitioning ratios between breast milk and serum for
305 PFASs. Based on current understanding of human exposure to PFOS and PFOA, the major
306 contributor to our predicted additional exposures is likely to be the diet. However, we
307 highlight that other exposure pathways such as dermal uptake of PFASs from fabrics and
308 cosmetics may also contribute considerably to human exposure. Research to characterise the
309 exposure of the Irish population to PFASs via the diet and dermal uptake is thus
310 recommended.

311

312 **Conclusions**

313 PFOA, PFOS, PFNA, and PFHxS are present in Irish human milk, indicating ubiquitous
314 exposure of the Irish population to these contaminants. This evidence of population-level
315 exposure to PFNA and PFHxS adds urgency to the EFSA's ongoing assessment of the risks
316 of exposure to PFASs additional to PFOS and PFOA. Concentrations in human milk in
317 Ireland fall within the range of those reported previously for other countries, and exposure to

318 PFASs of Irish nursing infants via consumption of human milk does not appear to constitute a
319 health concern. Also reassuring, application of a simple PK model predicts that even at the
320 maximum concentration of PFOS detected in human milk in this study, the level of exposure
321 required to support this body burden in mothers is below EFSA's provisional TWI. In
322 contrast, applying the same approach to PFOA, suggests that the maximum concentration of
323 PFOA in human milk reported here, is consistent with maternal exposure above the
324 provisional TWI for this compound. These findings suggest detailed study of dietary and
325 dermal exposure to PFOS, PFOA and other PFASs in Ireland is required. Further research is
326 also recommended to enhance scientific knowledge of factors such as: partitioning ratios
327 between human milk and blood serum, as well as bioavailability and human half-lives for
328 PFASs.

329

330 **Acknowledgments**

331 This project (ELEVATE, reference 2016-HW-MS-8) is funded under the EPA Research
332 Programme 2014-2020. The EPA Research Programme is a Government of Ireland initiative
333 funded by the Department of Communications, Climate Action and Environment. We
334 gratefully acknowledge all the mothers who donated milk samples for this study.

335

336 **APPENDIX A. SUPPLEMENTARY DATA**

337 Supplementary data to this article can be found at...

338

339 **References**

340 Alves, R. N., Maulvault, A.L., Barbosa, V. L., Cunha, S., Kwadijk, C. J. A. F., Alvarez-
341 Munoz, D., Rodríguez-Mozaz, S., Aznar-Alemany, O., Eljarrat, E., Barcelo, D.,
342 Fernandez-Tejedor, M., Tediosi, A., Marques, A., 2017. Preliminary assessment on the

343 bioaccessibility of contaminants of emerging concern in raw and cooked seafood. *Fd.*
344 *Chem. Toxicol.* 104, 69-78.

345 Barbarossa, A., Masetti, R., Gazzotti, T., Zama, D., Astolfi, A., Veyrand, B., Pagliuca, G.,
346 2013. Perfluoroalkyl substances in human milk: A first survey in Italy. *Environ. Int.* 51,
347 27–30.

348 Bartell, S. M., Calafat, A. M., Lyu, C., Kato, K., Ryan, P. B., Steenland, K., 2010. Rate of
349 decline in serum PFOA concentrations after granulated activated carbon filtration at two
350 public water systems in Ohio and West Virginia. *Environ. Hlth. Perspect.* 118,156-164.

351 Buck, R. C., Franklin, J., Berger, U., Conder, J. M., Cousins, I. T., de Voogt, P., Jensen, A.
352 A., Kannan, K., Mabury, S. A., van Leeuwen, S. P., 2011. Perfluoroalkyl and
353 polyfluoroalkyl substances in the environment: Terminology, classification, and origins
354 *Integr. Environ. Assess. Manage.* 7, 513-541.

355 Central Statistics Office, 2018. Vital Statistics First Quarter 2018 [WWW Document]. CSO
356 Stat. Publ. URL [https://www.cso.ie/en/releasesandpublications/ep/p-](https://www.cso.ie/en/releasesandpublications/ep/p-vs/vitalstatisticsfirstquarter2018/)
357 [vs/vitalstatisticsfirstquarter2018/](https://www.cso.ie/en/releasesandpublications/ep/p-vs/vitalstatisticsfirstquarter2018/) (accessed 7th April 2019).

358 Chaemfa, C., Barber, J.L. Huber, S., Breivik, K., Jones, K.C., 2010. Screening for PFOS and
359 PFOA in European air using passive samplers. *J. Environ. Monit.* 12, 1100–1109.

360 Croes, K., Colles, A., Koppen, G. Govarts, E. Bruckers, L. Van de Mieroop, E.
361 Nelen, V. Covaci, A. Dirtu, A.C. Thomsen, C. Haug, L.S. Becher, G. Mampaey, M.,
362 Schoeters, G., Van Larebeke, N. Baeyens. W., 2012. Persistent organic pollutants (POPs)
363 in human milk: A biomonitoring study in rural areas of Flanders (Belgium).
364 *Chemosphere*, 89, 988-994

365 ECHA (European Chemicals Agency) 2019 Candidate List of substances of very high
366 concern for authorisation. <https://echa.europa.eu/candidate-list-table>. (Accessed 26th July
367 2019).

368 EFSA (European Food Safety Authority), 2018. Panel on Contaminants in the Food Chain
369 (CONTAM), Risk to human health related to the presence of perfluorooctane sulfonic acid
370 and perfluorooctanoic acid in food. *EFSA J.* 16, 5194.

371 Fång, J., Nyberg, E., Winnberg, U., Bignert, A., Bergman, Å. 2015 Spatial and temporal
372 trends of the Stockholm Convention POPs in mothers' milk — a global review *Environ*
373 *Sci Pollut Res* 22, 8989–9041.

374 Guzmàn, M.M., Clementini, C., Pérez-Cárceles, M.D., Rejón, S.J., Cascone, A., Martellini,
375 T., Guerranti, C., Cincinelli, A., 2016. Perfluorinated carboxylic acids in human breast
376 milk from Spain and estimation of infant's daily intake. *Sci.Tot. Environ.* 544, 595–600.

377 Harrad, S., de Wit, C. A., Abdallah, M. A-E., Bergh, C., Björklund, J. A., Covaci, A.,
378 Darnerud, P. O., de Boer, J., Diamond, M., Huber, S., Leonards, P., Mandalakis, M.,
379 Östman, C., Småstuen Haug, L., Thomsen, C., Webster, T. F., 2010. Indoor
380 Contamination with Hexabromocyclododecanes, Polybrominated Diphenyl Ethers and
381 Perfluoroalkyl Compounds: An Important Exposure Pathway for People? *Environ. Sci.*
382 *Technol.* 44, 3221–3231.

383 Harrad, S., Drage, D. S., Sharkey, M., Berresheim, H., 2019a. Brominated flame retardants
384 and perfluoroalkyl substances in landfill leachate from Ireland *Sci. Tot. Environ.* 695,
385 133810.

386 Harrad, S., Wemken, N., Drage, D. S., Abdallah, M. A-E., Coggins, A. M., 2019b.
387 Perfluoroalkyl Substances in Drinking Water, Indoor Air and Dust from Ireland:
388 Implications for Human Exposure. *Environ. Sci. Technol.* 53, 13449–13457.

389 Haug, L. S., Huber, S., Becher, G., Thomsen, C., 2011. Characterisation of human exposure
390 pathways to perfluorinated compounds – Comparing exposure estimates with biomarkers
391 of exposure. *Environ. Int.* 37, 687-693.

392 Jian, J.M., Guo, Y., Zeng, L., Liang-Ying, L., Lu, X., Wang, F., Zeng, E.Y., 2017. Global
393 distribution of perfluorochemicals (PFCs) in potential human exposure sources - A review.
394 Environ. Int. 108, 51-62.

395 Kang, H., Choi, K., Lee, H-S., Kim, D-H., Park, N-Y., Kim, S., Kho, Y., 2016. Elevated
396 levels of short-carbon chain PFCAs in breast milk among Korean women: Current status
397 and potential challenges, Environ. Res. 148, 351-359.

398 Kärman, A., Ericson, I., van Bavel, B., Lindström, G., 2006. Analysis and Occurrence of
399 Perfluorinated Chemicals in Breast Milk and Serum from Swedish Women, 1996-2005
400 (No. dnr 721-1554-04Mm). Örebro universitet, Människa-Teknik-Miljö
401 forskningscentrum. Retrieved from urn
402 <http://urn.kb.se/resolve?urn=urn:nbn:se:naturvardsverket:diva-249> accessed 17th
403 September 2019.

404 Lankova, D., Lacina, O., Pulkrabova, J., Hajslova, J., 2013. The determination of
405 perfluoroalkyl substances, brominated flame retardants and their metabolites in human
406 breast milk and infant formula. Talanta 117, 318–325

407 Lee, S., Kim, S., Park, J., Kim, H-J., Choi, G., Choi, S., Kim, S., Kim, S.Y., Choi, K., Moon,
408 H. B., 2018. Perfluoroalkyl substances (PFASs) in breast milk from Korea: Time-course
409 trends, influencing factors, and infant exposure. Sci.Tot. Environ. 612, 286–292.

410 Li, K., Li, C., Yu, N-Y., Juhasz, A. L., Cui, X-Y., Ma, L. Q., 2015. In Vivo Bioavailability
411 and In Vitro Bioaccessibility of Perfluorooctanoic Acid (PFOA) in Food Matrices:
412 Correlation Analysis and Method Development. Environ. Sci. Technol. 49, 150–158.

413 Lindstrom, A.B., Mark, J., Strynar, M.J., Libelo, E.L., 2011. Polyfluorinated compounds:
414 past, present, and future. Environ. Sci. Technol. 45, 7954–7961.

415 Liu, J., Li, J., Liu, Y., Chan, H. M., Zhao, Y., Cai, Z., Wu, Y., 2011. Comparison on gestation
416 and lactation exposure of perfluorinated compounds for newborns. Environ. Int. 37, 1206–

417 1212.

418 Olsen, G. W., Burris, J. M., Ehresman, D. J., Forelich, J. W., Seacat, A. M., Butenhoff, J. L.,
419 Zobel, L. R., 2007. Half-life of serum elimination of perfluorooctanesulfonate,
420 perfluorohexanesulfonate, and perfluorooctanoate in retired fluorochemical production
421 workers. *Environ. Hlth. Perspect.* 115, 1298-1305.

422 Pratt, I., Anderson, W., Crowley, D., Daly, S., Evans, R., Fernandes, A., Fitzgerald, M.,
423 Geary, M., Keane, D., Morrison, J.J., Reilly, A., Tlustos, C., 2013. Brominated and
424 fluorinated organic pollutants in the breast milk of first-time Irish mothers: is there a
425 relationship to levels in food? *Fd. Addit. Contam. A* 30, 1788–1798.

426 Sonne, C., 2010. Health effects from long-range transported contaminants in Arctic top
427 predators: an integrated review based on studies of polar bears and relevant model species.
428 *Environ. Int.* 36, 461–491.

429 Stockholm Convention, 2009. Stockholm Convention on Persistent Organic Pollutants
430 (POPs) as Amended in 2009. Decision SC-4/17, Geneva, Switzerland.
431 [http://chm.pops.int/TheConvention/Overview/TextoftheConvention/tabid/2232/Default.as](http://chm.pops.int/TheConvention/Overview/TextoftheConvention/tabid/2232/Default.aspx)
432 [px.](http://chm.pops.int/TheConvention/Overview/TextoftheConvention/tabid/2232/Default.aspx) (Accessed 26th July 2019).

433 Sundström, M., Ehresman, D. J., Bignert, A., Butenhoff, J. L., Olsen, G. W., Chang, S-C.,
434 Bergman, Å., 2011. A temporal trend study (1972-2008) of perfluorooctanesulfonate,
435 perfluorohexanesulfonate, and perfluorooctanoate in pooled human milk samples from
436 Stockholm, Sweden. *Environ. Int.* 37, 178–183.

437 Thompson, J., Lorber, M., Toms, L-M. L., Kato, K., Calafat, A.M., Mueller, J. F., 2010. Use
438 of simple pharmacokinetic modeling to characterize exposure of Australians to
439 perfluorooctanoic acid and perfluorooctane sulfonic acid. *Environ. Int.* 36, 390–397.

440 USEPA, 2002. Exposure Factors Handbook. Washington, DC. [https://doi.org/EPA/600/R-](https://doi.org/EPA/600/R-06/096F)
441 [06/096F.](https://doi.org/EPA/600/R-06/096F)

442 Wemken, N., Drage, D.S., Abdallah, M.A.E., Harrad, S., Coggins, M., 2019. Concentrations
443 of Brominated Flame Retardants in Indoor Air and Dust from Ireland reveal elevated
444 exposure to Decabromodiphenyl Ethane. *Environ. Sci. Technol.* 53, 9826-9836.

445 Wemken, N., Drage, D. S., Cellarius, C., Cleere, K., Morrison, J. J., Daly, S., Abdallah, M.
446 A.-E., Tlustos, C., Harrad, S., Coggins, M. A., 2020. Emerging and legacy brominated
447 flame retardants in the breast milk of first time Irish mothers suggest positive response to
448 restrictions on use of HBCDD and Penta- and Octa-BDE formulations. *Environ. Res.* 180,
449 108805.

450 WHO (World Health Organisation), 2007. 4th WHO-coordinated survey of human milk for
451 persistent organic pollutants in cooperation with UNEP. Guidelines for developing a
452 national protocol. WHO Geneva, Switzerland.

453 Zhao, Y.G., Wong, C.K.C., Wong, M.H., 2012. Environmental contamination, human
454 exposure and body loadings of perfluorooctane sulfonate (PFOS), focusing on Asian
455 countries. *Chemosphere* 89, 355–368.

456 **Table 1: Descriptive statistics^a for concentrations (ng/mL) of PFASs in Irish human**
 457 **milk from primiparas (ng/mL; n=16 pooled samples) and comparison with**
 458 **concentrations from other studies worldwide**

| Parameter (Country, year of sample collection, reference) | PFOA | PFHxS | PFOS | PFNA |
|---|-------------|--------------|-------------|-------------|
| Detection frequency, % (this study) | 100 | 31 | 62 | 69 |
| Arithmetic Mean (this study) | 0.13 | <0.04 | 0.038 | 0.026 |
| Median (this study) | 0.10 | <0.04 | 0.02 | 0.014 |
| Minimum (this study) | 0.016 | <0.04 | <0.02 | <0.01 |
| Maximum (this study) | 0.35 | 0.087 | 0.12 | 0.1 |
| 5 th percentile (this study) | 0.04 | <0.04 | <0.02 | <0.01 |
| 95 th percentile (this study) | 0.35 | 0.08 | 0.085 | 0.075 |
| Median (S. Korea, 2013; Kang et al, 2016) | 0.07 | - | 0.050 | <0.022 |
| Range of medians (from 13 countries, 1995-2011 ^b ; Fång et al, 2015) | - | - | 0.04-0.20 | - |
| Median (Belgium, 2009-2010; Croes et al, 2012) | 0.07 | <0.01 | 0.10 | <0.01 |
| Arithmetic mean (Sweden, 2008; Sundström et al, 2011) | 0.074 | 0.014 | 0.075 | - |
| Median (China, 2009; Liu et al, 2011) | 0.12 | - | 0.042 | 0.019 |
| Median (S. Korea, 2011; Lee et al, 2018) | 0.039 | - | 0.047 | 0.015 |
| Median (Spain, 2014; Guzman et al, 2016) | 0.049 | - | - | 0.066 |
| Arithmetic Mean (Italy, 2010; Barbarossa et al, 2013) | 0.076 | - | 0.057 | - |
| Median (Czech Republic, 2010; Lankova et al, 2013) | 0.044 | <0.006 | 0.047 | <0.006 |

459 ^a Values below LOQ were assumed to = LOQ*fractional detection frequency

460 ^b denotes range of years in which covered studies were published

461 **Table 2: Estimated exposure^a (ng/kg bw/day) of a 1-month old nursing infant to PFASs**
462 **in Irish human milk**

| PFAS | 95th percentile | Median |
|-------------|---------------------------------------|---------------|
| PFOA | 59 | 18 |
| PFHxS | 14 | 2.1 |
| PFOS | 14 | 3.5 |
| PFNA | 13 | 2.4 |

463 ^a Assuming a daily breast milk intake of 702 mL/day, a body weight of 4.14 kg (U.S. EPA,
464 2002), and consumption of breast milk contaminated at either the median or 95th percentile
465 concentration in this study

466 **Table 3: Predicted daily intakes of PFOS and PFOA (pg/kg bw/day) required to support**
 467 **observed concentrations in Irish human milk**

| PFAS | Human milk concentration (ng/mL) | Predicted total intake^a | Non-dietary intake^b | Predicted additional intake^c | EFSA “TDI”^d |
|-------------|---|---|---------------------------------------|--|-------------------------------|
| PFOS | Average | 245 | 1.6 | 244 | 1857 |
| | Median | 136 | 2.0 | 134 | 1857 |
| | Minimum | 67 | 0.6 | 66 | 1857 |
| | Maximum | 799 | 71 | 728 | 1857 |
| PFOA | Average | 591 | 30 | 561 | 857 |
| | Median | 474 | 30 | 444 | 857 |
| | Minimum | 73 | 1.4 | 72 | 857 |
| | Maximum | 1610 | 132 | 1478 | 857 |

468 ^aSum of intakes from all pathways

469 ^bMeasured data from Harrad et al (2019b) covering inhalation of indoor air and ingestion of
 470 indoor dust and drinking water

471 ^cSum of intakes from all pathways minus inhalation of indoor air and ingestion of indoor dust
 472 and drinking water

473 ^dEFSA’s tolerable weekly intake converted for the purposes of comparison only to tolerable
 474 daily intake

Supplementary Material

[Click here to download Supplementary Material: Supplementary Data.docx](#)

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