Bogdan *et al. J Environ Expo Assess* 2024;3:13
DOI: 10.20517/jeea.2024.08

Journal of Environmental Exposure Assessment

Supplementary Materials

Per- and polyfluoroalkyl substances (PFAS) in powdered infant formula: potential exposures and health risks

Alexander R Bogdan[1], Kristine S Klos[1], Christopher W Greene[1], Carin A Huset[2], Kitrina M Barry[2], Helen M Goeden[3]

[1]Health Risk Assessment Unit, Minnesota Department of Health, St. Paul, MN 55164-0975, USA.

[2]Public Health Laboratory, Minnesota Department of Health, St. Paul, MN 55164-0975, USA.

[3]Health Risk Assessment Unit (retired), Minnesota Department of Health, St. Paul, MN 55164-0975, USA.

Correspondence to: Alexander R Bogdan, Minnesota Department of Health, 625 Robert St. N, P.O. Box 64975, St. Paul, MN, 55164-0975, USA. E-mail: alex.bogdan@state.mn.us

Supplementary Table 1. Powdered infant formulas included in the study

Brand	Product	Protein Source	Properties/Dietary Need
Bobbie	Organic Infant Formula	Dairy	Standard
Earth's Best	Organic Dairy Infant Formula	Dairy	Standard
Earth's Best	Non-GMO Soy Infant Formula	Soy	Dairy/Lactose intolerance and Galactosemia
Enfamil	Gentlease*	Dairy	Lactose sensitivity
Enfamil	A.R.*	Dairy	Added rice to prevent spit-up
Enfamil	EnfaCare NeuroPro*	Dairy	Premature infants
Enfamil	Nutramigen*	Dairy	Hypoallergenic; amino acid (hydrolyzed milk protein)
Gerber	Good Start GentlePro Non-GMO*	Dairy	Protein sensitivity
Gerber	Good Start Soy Non-GMO*	Soy	Dairy/Lactose intolerance
HappyBaby	Organic Infant Formula	Dairy	Standard
Nutricia	Neocate	Amino Acid	Hypoallergenic; amino acid (made from individual amino acids rather than hydrolyzed casein from milk)
Similac	Advance*	Dairy	Standard
Similac	Sensitive Baby*	Dairy	Lactose sensitivity
Similac	Soy Isomil*	Soy	Lactose intolerance/galacosemia
Similac	Neosure Premature Post-Discharge*	Dairy	Premature infants
Up and Up	Soy Powder Infant Formula	Soy	Dairy/Lactose intolerance and Galactosemia
Up and Up	Gentle Infant Formula	Dairy	Lactose sensitivity

*Selected from WIC Program purchasing statistics. GMO, Genetically-Modified Organism; WIC, Special Supplemental Nutrition Program for Women, Infants, and Children.

Supplementary Table 2. References consulted for PFOS placental transfer factors

	Reference for Placental Transfer Factor	Mean	Median	Upper Percentile
1.	Inoue K, Okada F, Ito R, Kato S, Sasaki S, Nakajima S, Uno A, Saijo Y, Sata F, Yoshimura Y, Kishi R, Nakazawa H. Perfluorooctane sulfonate (PFOS) and related perfluorinated compounds in human maternal and cord blood samples: assessment of PFOS exposure in a susceptible population during pregnancy. Environ Health Perspect. 2004 Aug;112(11):1204-7. doi: 10.1289/ehp.6864. PMID: 15289168; PMCID: PMC1247483.	0.32	0.31	0.39
2.	Midasch O, Drexler H, Hart N, Beckmann MW, Angerer J. Transplacental exposure of neonates to perfluorooctanesulfonate and perfluorooctanoate: a pilot study. Int Arch Occup Environ Health. 2007 Jul;80(7):643-8. doi: 10.1007/s00420-006-0165-9. Epub 2007 Jan 12. PMID: 17219182.	0.6	0.58	0.79
3.	Fei C, McLaughlin JK, Tarone RE, Olsen J. Perfluorinated chemicals and fetal growth: a study within the Danish National Birth Cohort. Environ Health Perspect. 2007 Nov;115(11):1677-82. doi: 10.1289/ehp.10506. PMID: 18008003; PMCID: PMC2072850.	0.34		
4.	Monroy R, Morrison K, Teo K, Atkinson S, Kubwabo C, Stewart B, Foster WG. Serum levels of perfluoroalkyl compounds in human maternal and umbilical cord blood samples. Environ Res. 2008 Sep;108(1):56-62. doi: 10.1016/j.envres.2008.06.001. Epub 2008 Jul 22. PMID: 18649879.	0.44	0.42	
5.	Fromme H, Mosch C, Morovitz M, Alba-Alejandre I, Boehmer S, Kiranoglu M, Faber F, Hannibal I, Genzel-Boroviczény O, Koletzko B, Völkel W. Pre- and postnatal exposure to perfluorinated compounds (PFCs). Environ Sci Technol. 2010 Sep 15;44(18):7123-9. doi: 10.1021/es101184f. PMID: 20722423.	0.3		
6.	Needham LL, Grandjean P, Heinzow B, Jørgensen PJ, Nielsen F, Patterson DG Jr, Sjödin A, Turner WE, Weihe P. Partition of environmental chemicals between maternal and fetal blood and tissues. Environ Sci Technol. 2011 Feb 1;45(3):1121-6. doi: 10.1021/es1019614. Epub 2010 Dec 17. PMID: 21166449; PMCID: PMC3031182.		0.34	
7.	Liu J, Li J, Liu Y, Chan HM, Zhao Y, Cai Z, Wu Y. Comparison on gestation and lactation exposure of perfluorinated compounds for newborns. Environ Int. 2011 Oct;37(7):1206-12. doi: 10.1016/j.envint.2011.05.001. Epub 2011 May 26. PMID: 21620474.	0.57	0.54	

Reference for Placental Transfer Factor	Mean	Median	Upper Percentile
8. Kim SK, Lee KT, Kang CS, Tao L, Kannan K, Kim KR, Kim CK, Lee JS, Park PS, Yoo YW, Ha JY, Shin YS, Lee JH. Distribution of perfluorochemicals between sera and milk from the same mothers and implications for prenatal and postnatal exposures. Environ Pollut. 2011 Jan;159(1):169-174. doi: 10.1016/j.envpol.2010.09.008. Epub 2010 Oct 6. PMID: 20932617.	0.36		0.56
9. Kim S, Choi K, Ji K, Seo J, Kho Y, Park J, Kim S, Park S, Hwang I, Jeon J, Yang H, Giesy JP. Trans-placental transfer of thirteen perfluorinated compounds and relations with fetal thyroid hormones. Environ Sci Technol. 2011 Sep 1;45(17):7465-72. doi: 10.1021/es202408a. Epub 2011 Aug 12. PMID: 21805959.	0.48	0.38	1.17
10. Gützkow KB, Haug LS, Thomsen C, Sabaredzovic A, Becher G, Brunborg G. Placental transfer of perfluorinated compounds is selective--a Norwegian Mother and Child sub-cohort study. Int J Hyg Environ Health. 2012 Feb;215(2):216-9. doi: 10.1016/j.ijheh.2011.08.011. Epub 2011 Sep 19. PMID: 21937271.	0.33	0.31	90th=0.49
11. Porpora MG, Lucchini R, Abballe A, Ingelido AM, Valentini S, Fuggetta E, Cardi V, Ticino A, Marra V, Fulgenzi AR, De Felip E. Placental transfer of persistent organic pollutants: a preliminary study on mother-newborn pairs. Int J Environ Res Public Health. 2013 Feb 7;10(2):699-711. doi: 10.3390/ijerph10020699. PMID: 23435591; PMCID: PMC3635171.	0.46		
12. Ode A, Rylander L, Lindh CH, Källén K, Jönsson BA, Gustafsson P, Olofsson P, Ivarsson SA, Rignell-Hydbom A. Determinants of maternal and fetal exposure and temporal trends of perfluorinated compounds. Environ Sci Pollut Res Int. 2013 Nov;20(11):7970-8. doi: 10.1007/s11356-013-1573-5. Epub 2013 Feb 24. PMID: 23436123.	0.45	0.43	0.75
13. Lee YJ, Kim MK, Bae J, Yang JH. Concentrations of perfluoroalkyl compounds in maternal and umbilical cord sera and birth outcomes in Korea. Chemosphere. 2013 Feb;90(5):1603-9. doi: 10.1016/j.chemosphere.2012.08.035. Epub 2012 Sep 16. PMID: 22990023.	0.35	0.32	0.73
14. Hanssen L, Dudarev AA, Huber S, Odland JØ, Nieboer E, Sandanger TM. Partition of perfluoroalkyl substances (PFASs) in whole blood and plasma, assessed in maternal and umbilical cord samples from inhabitants of arctic Russia and Uzbekistan. Sci Total Environ. 2013 Mar 1;447:430-7. doi: 10.1016/j.scitotenv.2013.01.029. Epub 2013 Feb 11. PMID: 23410865.		0.35	
15. Zhang T, Sun H, Lin Y, Qin X, Zhang Y, Geng X, Kannan K. Distribution of poly- and perfluoroalkyl substances in matched samples from pregnant women and carbon chain length related maternal transfer. Environ Sci Technol. 2013 Jul 16;47(14):7974-81. doi: 10.1021/es400937y. Epub 2013 Jul 2. PMID: 23777259.	0.21	0.21	

Reference for Placental Transfer Factor	Mean	Median	Upper Percentile
16. Kato K, Wong LY, Chen A, Dunbar C, Webster GM, Lanphear BP, Calafat AM. Changes in serum concentrations of maternal poly- and perfluoroalkyl substances over the course of pregnancy and predictors of exposure in a multiethnic cohort of Cincinnati, Ohio pregnant women during 2003-2006. Environ Sci Technol. 2014 Aug 19;48(16):9600-8. doi: 10.1021/es501811k. Epub 2014 Jul 29. PMID: 25026485; PMCID: PMC4140533.	0.4		
17. Cariou R, Veyrand B, Yamada A, Berrebi A, Zalko D, Durand S, Pollono C, Marchand P, Leblanc JC, Antignac JP, Le Bizec B. Perfluoroalkyl acid (PFAA) levels and profiles in breast milk, maternal and cord serum of French women and their newborns. Environ Int. 2015 Nov;84:71-81. doi: 10.1016/j.envint.2015.07.014. Epub 2015 Jul 29. PMID: 26232143.	0.38		0.7
18. Wilhelm M, Wittsiepe J, Völkel W, Fromme H, Kasper-Sonnenberg M. Perfluoroalkyl acids in children and their mothers: Association with drinking water and time trends of inner exposures--Results of the Duisburg birth cohort and Bochum cohort studies. Int J Hyg Environ Health. 2015 Oct;218(7):645-55. doi: 10.1016/j.ijheh.2015.07.001. Epub 2015 Jul 9. PMID: 26212496.		0.3	
19. Yang L, Wang Z, Shi Y, Li J, Wang Y, Zhao Y, Wu Y, Cai Z. Human placental transfer of perfluoroalkyl acid precursors: Levels and profiles in paired maternal and cord serum. Chemosphere. 2016 Feb;144:1631-8. doi: 10.1016/j.chemosphere.2015.10.063. Epub 2015 Oct 28. PMID: 26517392.	0.45	0.41	
20. Yang L, Li J, Lai J, Luan H, Cai Z, Wang Y, Zhao Y, Wu Y. Placental Transfer of Perfluoroalkyl Substances and Associations with Thyroid Hormones: Beijing Prenatal Exposure Study. Sci Rep. 2016 Feb 22;6:21699. doi: 10.1038/srep21699. PMID: 26898235; PMCID: PMC4762009.	0.36	0.29	1.06
21. Morello-Frosch R, Cushing LJ, Jesdale BM, Schwartz JM, Guo W, Guo T, Wang M, Harwani S, Petropoulou SE, Duong W, Park JS, Petreas M, Gajek R, Alvaran J, She J, Dobraca D, Das R, Woodruff TJ. Environmental Chemicals in an Urban Population of Pregnant Women and Their Newborns from San Francisco. Environ Sci Technol. 2016 Nov 15;50(22):12464-12472. doi: 10.1021/acs.est.6b03492. Epub 2016 Oct 26. PMID: 27700069; PMCID: PMC6681912.		0.8	
22. Zhao L, Zhang Y, Ma X, Wang Y, Sun H, Luo Y. Isomer-Specific Transplacental Efficiencies of Perfluoroalkyl Substances in Human Whole Blood. Environ Sci Technol Letters. 2017 4 (10), 391-398 doi: 10.1021/acs.estlett.7b00334	0.22	0.2	0.39

Reference for Placental Transfer Factor	Mean	Median	Upper Percentile
23. Pan Y, Zhu Y, Zheng T, Cui Q, Buka SL, Zhang B, Guo Y, Xia W, Yeung LW, Li Y, Zhou A, Qiu L, Liu H, Jiang M, Wu C, Xu S, Dai J. Novel Chlorinated Polyfluorinated Ether Sulfonates and Legacy Per-/Polyfluoroalkyl Substances: Placental Transfer and Relationship with Serum Albumin and Glomerular Filtration Rate. Environ Sci Technol. 2017 Jan 3;51(1):634-644. doi: 10.1021/acs.est.6b04590. Epub 2016 Dec 22. PMID: 27931097.	0.34	0.35	0.52
24. Chen F, Yin S, Kelly BC, Liu W. Chlorinated Polyfluoroalkyl Ether Sulfonic Acids in Matched Maternal, Cord, and Placenta Samples: A Study of Transplacental Transfer. Environ Sci Technol. 2017 Jun 6;51(11):6387-6394. doi: 10.1021/acs.est.6b06049. Epub 2017 May 12. PMID: 28482666.	0.43	0.40	[max 0.77]
25. Chen F, Yin S, Kelly BC, Liu W. Isomer-Specific Transplacental Transfer of Perfluoroalkyl Acids: Results from a Survey of Paired Maternal, Cord Sera, and Placentas. Environ Sci Technol. 2017 May 16;51(10):5756-5763. doi: 10.1021/acs.est.7b00268. Epub 2017 May 1. PMID: 28434222.			
26. Wang Y, Han W, Wang C, Zhou Y, Shi R, Bonefeld-Jørgensen EC, Yao Q, Yuan T, Gao Y, Zhang J, Tian Y. Efficiency of maternal-fetal transfer of perfluoroalkyl and polyfluoroalkyl substances. Environ Sci Pollut Res Int. 2019 Jan;26(3):2691-2698. doi: 10.1007/s11356-018-3686-3. Epub 2018 Nov 27. PMID: 30484044.		0.3	0.63
27. Han W, Gao Y, Yao Q, Yuan T, Wang Y, Zhao S, Shi R, Bonefeld-Jorgensen EC, Shen X, Tian Y. Perfluoroalkyl and polyfluoroalkyl substances in matched parental and cord serum in Shandong, China. Environ Int. 2018 Jul;116:206-213. doi: 10.1016/j.envint.2018.04.025. Epub 2018 Apr 23. PMID: 29698897.		0.31	
28. Gao K, Zhuang T, Liu X, Fu J, Zhang J, Fu J, Wang L, Zhang A, Liang Y, Song M, Jiang G. Prenatal Exposure to Per- and Polyfluoroalkyl Substances (PFASs) and Association between the Placental Transfer Efficiencies and Dissociation Constant of Serum Proteins-PFAS Complexes. Environ Sci Technol. 2019 Jun 4;53(11):6529-6538. doi: 10.1021/acs.est.9b00715. Epub 2019 May 23. PMID: 31099564.	0.44		
29. Eryasa B, Grandjean P, Nielsen F, Valvi D, Zmirou-Navier D, Sunderland E, Weihe P, Oulhote Y. Physico-chemical properties and gestational diabetes predict transplacental transfer and partitioning of perfluoroalkyl substances. Environ Int. 2019 Sep;130:104874. doi: 10.1016/j.envint.2019.05.068. Epub 2019 Jun 11. PMID: 31200157; PMCID: PMC7029428.		0.38	Max ratio 3.87

Reference for Placental Transfer Factor	Mean	Median	Upper Percentile
30. Li J, Cai D, Chu C, Li Q, Zhou Y, Hu L, Yang B, Dong G, Zeng X, Chen D. Transplacental Transfer of Per- and Polyfluoroalkyl Substances (PFASs): Differences between Preterm and Full-Term Deliveries and Associations with Placental Transporter mRNA Expression. Environ Sci Technol. 2020 Apr 21;54(8):5062-5070. doi: 10.1021/acs.est.0c00829. Epub 2020 Apr 1. PMID: 32208722.		0.58	Q3 0.96
31. Cai D, Li QQ, Chu C, Wang SZ, Tang YT, Appleton AA, Qiu RL, Yang BY, Hu LW, Dong GH, Zeng XW. High trans-placental transfer of perfluoroalkyl substances alternatives in the matched maternal-cord blood serum: Evidence from a birth cohort study. Sci Total Environ. 2020 Feb 25;705:135885. doi: 10.1016/j.scitotenv.2019.135885. Epub 2019 Dec 2. PMID: 31841927.	0.51	0.42	1.25
32. Liu Y, Liu K, Zheng P, Yin S, Jin H, Bai X, Li Y, Zheng J, Dai Y, Zhao M, Liu W. Prenatal exposure and transplacental transfer of perfluoroalkyl substance isomers in participants from the upper and lower reaches of the Yangtze River. Environ Pollut. 2021 Feb 1;270:116202. doi: 10.1016/j.envpol.2020.116202. Epub 2020 Dec 6. PMID: 33333405.	0.38	0.38	0.7
33. Kaiser AM, Forsthuber M, Aro R, Kärrman A, Gundacker C, Zeisler H, Foessleitner P, Salzer H, Hartmann C, Uhl M, Yeung LWY. Extractable Organofluorine Analysis in Pooled Human Serum and Placental Tissue Samples from an Austrian Subpopulation-A Mass Balance Analysis Approach. Environ Sci Technol. 2021 Jul 6;55(13):9033-9042. doi: 10.1021/acs.est.1c00883. Epub 2021 Jun 16. PMID: 34133125; PMCID: PMC8277134.		0.41	Max ratio 0.78
34. Gundacker C, Graf-Rohrmeister K, Gencik M, Hengstschläger M, Holoman K, Rosa P, Kroismayr R, Offenthaler I, Plichta V, Reischer T, Teufl I, Raffesberg W, Scharf S, Köhler-Vallant B, Delissen Z, Weiß S, Uhl M. Gene Variants Determine Placental Transfer of Perfluoroalkyl Substances (PFAS), Mercury (Hg) and Lead (Pb), and Birth Outcome: Findings From the UmMuKi Bratislava-Vienna Study. Front Genet. 2021 Jun 16;12:664946. doi: 10.3389/fgene.2021.664946. PMID: 34220941; PMCID: PMC8242356.		0.24	Q3 = 0.3
35. Li Y, Lu X, Yu N, Li A, Zhuang T, et al. Exposure to legacy and novel perfluoroalkyl substance disturbs the metabolic homeostasis in pregnant women andfetuses: a metabolome-wide association study. Environment International 2021;156:106627. doi: 10.1016/j.envint.2021.106627	0.47		
36. Kang H, Kim HS, Yoon YS, Lee J, Kho Y, Lee J, Chang HJ, Cho YH, Kim YA. Placental Transfer and Composition of Perfluoroalkyl Substances (PFASs): A Korean Birth Panel of Parent-Infant Triads. Toxics. 2021 Jul 14;9(7):168. doi: 10.3390/toxics9070168. PMID: 34357911; PMCID: PMC8309930.	0.12		

Reference for Placental Transfer Factor		Mean	Median	Upper Percentile
37. Zheng P, Liu Y, An Q, Yang X, Yin S, Ma LQ, Liu W. Prenatal and postnatal exposure to emerging and legacy per-/polyfluoroalkyl substances: Levels and transfer in maternal serum, cord serum, and breast milk. Sci Total Environ. 2022 Mar 15;812:152446. doi: 10.1016/j.scitotenv.2021.152446. Epub 2021 Dec 21. PMID: 34952085.		0.43	0.4	0.75
38. Bao J, Shao LX, Liu Y, Cui SW, Wang X, Lu GL, Wang X, Jin YH. Target analysis and suspect screening of per- and polyfluoroalkyl substances in paired samples of maternal serum, umbilical cord serum, and placenta near fluorochemical plants in Fuxin, China. Chemosphere. 2022 Nov;307(Pt 1):135731. doi: 10.1016/j.chemosphere.2022.135731. Epub 2022 Jul 14. PMID: 35843426.			0.3	
39. Zhang B, Wei Z, Gu C, Yao Y, Xue J, Zhu H, Kannan K, Sun H, Zhang T. First Evidence of Prenatal Exposure to Emerging Poly- and Perfluoroalkyl Substances Associated with E-Waste Dismantling: Chemical Structure-Based Placental Transfer and Health Risks. Environ Sci Technol. 2022 Dec 6;56(23):17108-17118. doi: 10.1021/acs.est.2c05925. Epub 2022 Nov 18. PMID: 36399367.		0.36	0.4	
	Count	27	29	14
	Min	0.12	0.20	0.39
	Max	0.60	0.80	1.25
	Mean	**0.39**	**0.38**	**0.74**
	Median	0.38	0.38	0.72
	95th percentile	0.55	0.58	1.20