Per- and Polyfluoroalkyl Substances: Toxic Chemicals of Concern in North Carolina

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Per- and polyfluoroalkyl substances (PFASs), a family of human-made chemicals often described as "forever chemicals," are observed in a wide range of products utilized by North Carolinians and can cause liver damage, cancer, and infertility. Owing to their widespread use and persistence in the environment, humans and animals are exposed to individual and combinations of PFASs.

Background

Per- and polyfluoroalkyl substances (PFASs) are persistent organic pollutants that have been widely used in consumer products for more than seven decades and can pose health risks to exposed individuals including liver damage, increased risk of thyroid disease, cancer, and a decrease in fertility [1, 2]. PFASs are a class of organic chemicals that have one fluorinated carbon atom at a minimum, are highly hydrophobic, and have strong water and oil repellent properties. PFASs are widely used in many applications, such as food packaging, firefighting foams, and coatings to bring about nonstick and stain-resistant properties in several household items [3]. PFASs are also used as lubricants in industrial processes and are additives in insecticides and pharmaceuticals. PFASs' water- and oil-repellent properties have also been used in carpeting, paper, and upholstery [3].

The major PFASs are resistant to environmental degradation and accumulate over time in tissues, with many having elimination half-lives in humans of several years [4]. Indeed, the carbon-fluorine bonds responsible for repellent effects are highly chemically and thermally stable, making PFASs remarkably resilient and consequently difficult to degrade and/or destroy. This resilience indicates that PFASs in the environment or body have environmental and physiological consequences for an extended time, hence the urgent need to identify, characterize, and understand the health consequences of PFASs to promote public and environmental health.

Factors in the home environment, including contaminated foods and house dust, are key sources of human exposure, with drinking water in areas of the United States and North Carolina also found to be contaminated with PFASs [5, 6]. Due to extensive exposure to PFASs from water, air, and food—in addition to the environmental and biological persistence of some PFASs—measurable levels of them can be found in the blood of a significant percentage of the population in developed and developing countries [4].

PFASs can bring forth varying adverse health effects, including liver damage, cancer, increased risk of thyroid disease, and decreased fertility, depending on the route of exposure and its magnitude and duration [1]. In addition, individual-level factors such as ethnicity, age, sex, genetic predisposition, and current health status potentially help determine adverse health outcomes [7].

Exposure to PFASs begins in-utero, where they readily cross the placental barrier [8]. Exposure can continue early in life with PFASs able to enter breast milk [8]; indeed, population studies have suggested that breastfeeding duration and milk quantity are adversely altered by PFASs exposure [9]. Exposure levels disproportionately affect children, with PFAS concentrations in young children generally exceeding maternal serum concentrations, which can lead to adverse effects such as obesity, hormone suppression, and thyroid diseases in childhood and over the lifespan [2]. These differences may be partly explained by children's hand-to-mouth behavior, which allows for increased exposure early in life [10].

In adults, PFASs adversely impact several systems within the human body, including the hepatic [11], inflammatory [12], metabolic [13], reproductive, neurological [14], and cardiovascular [15], by altering normal physiological processes toward dysfunction. Studies have found gender to be important for some exposure-health associations, with factors such as obesity potentially playing a role in differential PFAS exposure outcomes [16]. Factors such as breastfeeding and menstruation may also explain differences in body burden, with these processes serving as critical elimination routes for some PFASs [17, 18].

Studies on some PFAS effects on neurocognition are mixed, with some postulating a protective effect and others showing neurotoxic effects [19–21]. Epidemiological stud-

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ies have demonstrated that the effects of some PFASs on executive function may be potentially mediated by thyroid hormones in older adults [22].

Owing to PFASs' environmental and biological persistence and their effects on human health, it is imperative to understand their impact on North Carolina populations. For example, the half-life for PFASs can range from 1–5 years, meaning exposure can be long-lasting, and factors related to exposure must be identified to commence the process of prevention [23].

Studies in North Carolina

It must be noted that non-water sources of PFASs are more broadly distributed across North Carolina than water sources, and are therefore the likeliest trigger of exposure in the state. Indeed, PFAS levels in water are generally lower in Western North Carolina as compared to Central and Eastern areas of the state. That said, water is the most profound source of exposure owing to its essentiality for human function, widespread distribution, and critical impact on individual and public health.

PFASs likely exist in every North Carolina water body. The current available datasets for PFAS levels in North Carolina are the North Carolina Department of Environmental Quality (DEQ) drinking water data and wastewater treatment plant (WWTP) sampling data. These data affirm that the most extreme sources of PFAS exposure in North Carolina come from the aftereffects of the manufacturing process.

The legacy of manufacturing is the origin of PFAS water contamination in many areas in North Carolina [24], underscoring the urgent need to assess, characterize, and evaluate the consequences of the manufacturing processes in producing traditional and emerging contaminants. When DuPont began to produce perfluorooctanoic acid (PFOA) in response to a loss of supply from The 3M Company, exposure to PFASs increased in Wilmington, North Carolina. Eventually, PFOA use diminished due to health concerns. DuPont began manufacturing hexafluoropropylene oxide dimer acid (GenX) as a less-dangerous replacement for PFOA, though it was later discovered that it had detrimental effects similar to those of PFOA, such as adverse effects on the liver, thyroid, and immune system. News of these and other adverse effects became apparent to the public in the middle of 2017 when GenX was detected in the Cape Fear River, and its risks were widely revealed in the local Wilmington media. Chemours, a chemical company founded in July 2015 as a spinoff from DuPont, which owned the Fayetteville Works manufacturing site along the Cape Fear River, became the source of much coverage related to PFAS contamination. As a result, questions arose about safe exposure levels and the health consequences of exposure. Studies on PFASs in North Carolina have primarily focused on the Cape Fear River owing to the presence of legacy and emerging PFASs within it [25].

For nearly 40 years prior to 2017, wastewater containing unclearly defined PFASs was discharged into the Cape Fear River, the principal drinking water source for Wilmington. In a study by Kotlarz and colleagues examining PFASs in the serum of Wilmington residents, four legacy PFASs (PFOA, PFOS, perfluorohexane sulfonate-PFHxS, and perfluorononanoic acid-PFNA) exceeded the mean levels for the US population as specified by the National Health and Nutrition Examination Survey (NHANES) 2015–2016 [26]. In addition, the median serum concentration for PFOA exceeded the 95th percentile for the US population [26]. The authors speculated that drinking water sourced from the lower Cape Fear River was the reason for the elevated PFOA serum concentrations. In this study, fluoroethers, a type of PFAS, were present in a subset of samples, suggesting people with drinking water obtained from the lower Cape Fear River were exposed to PFASs in wastewater from the manufacturing facility.

North Carolina currently uses the standard of 70 parts per trillion (ppt), set by the US Environmental Protection Agency (EPA), for perfluorooctane sulfonate (PFOS) and PFOA, and has a statewide goal of less than 140 ppt for GenX in all state drinking water [27]. The exposure level at which non-cancer health effects would be expected in the most sensitive population over a lifetime of exposure is 140 ppt. The at-risk population includes infants who are bottle-fed, because they drink the largest volume of water per body weight. The EPA has not set advisory levels for any other PFAS chemical beyond PFOS and PFOA.

In a study by Bangma and colleagues examining 122 pregnant women in Chapel Hill, North Carolina, the team examined PFAS levels in the placenta to identify sociodemographic risk factors in the cohort [28]. Even though PFOS was phased out of production in the United States in 2002, this study found the presence of PFOS in the placenta, which highlights the persistence of PFASs and signifies the importance of continued PFAS monitoring and reduction efforts.

The study also found that PFOS, PFHxS, perfluoroheptanesulfonic acid-PFHpS, and perfluoroundecanoic acid-PFUnA were higher than the reporting limit in 99%, 75%, 55%, and 49% of examined placentas, respectively [28]. This suggests that PFAS exposure in this area occurs early in the life course and will subsequently have potential health effects on the exposed. The authors proposed performing biomonitoring for exposure to PFASs during pregnancy in North Carolina as a way to identify and mitigate exposure risks quickly. In the study, maternal race and ethnicity were associated with significant differences in PFUnA levels, with those who reported their race/ethnicity as Non-Hispanic White having the highest median measures of PFUnA, whereas Non-Hispanic Black women had the lowest measures [28]. That said, PFAS concentrations vary by race/ethnicity in most cohorts; depending on the PFASs being studied and the setting/location, higher levels may show up in different ethnicities, and different PFASs appear to show varied distributions by race and ethnicity.

In a study by Zhou and colleagues that measured PFAS concentrations of ambient fine particulate matter ($PM_{2.5}$)

at five locations in North Carolina (Fayetteville, Research Triangle Park, Greenville, Wilmington, Charlotte) over a one-year period in 2019, 34 PFASs, including perfluoroalkyl carboxylic, perfluoroalkane sulfonic, perfluoroalkyl ether carboxylic, and sulfonic acids, were analyzed [29]. Measures of PFOA and PFOS were comparable to previous $PM_{2.5}$ measurements from Canada and Europe. Concentrations above 1 picogram per cubic meter (pg m^{-3}) were observed in July–September in Charlotte (14.1 pg m^{-3}, PFOA), Wilmington (4.75 pg m^{-3}, PFOS), and Research Triangle Park (1.37 pg m^{-3}, PFOS) [29].

Concentration values that differ across locations suggest local sources—primary emissions from legacy materials, atmospheric (secondary) formation, and bubble bursting/wave breaking from coastal waters contaminated by the Cape Fear River—play an essential role in PFAS contamination. When bubbles burst on the ocean surface, they scavenge surface-active materials, including PFASs, from the sea surface microlayer. Therefore, bubble bursting or wave breaking of PFAS-contaminated coastal ocean water is a plausible cause of elevated PFOS in Wilmington.

In a public health epidemiologic surveillance report by Pritchett and colleagues examining the serum and urine specimens from a convenience sample of residents near a chemical manufacturing facility that dumped PFASs into the Cape Fear River, nine PFASs were identified in serum [30]. Perfluorohexane sulfonic acid and linear perfluorooctane sulfonic acid had median serum concentrations that were markedly higher than were those in NHANES participants. The other seven PFASs were found at concentrations similar to or lower than those in NHANES data [30].

Seasonality is a critical factor in several PFAS exposure levels, with the summer months posing the highest exposure risk [29]. In addition, groundwater can carry contaminants and further the distribution of pollutants if connected to other sources. Thus, the potential health risk of PFAS exposure can persist even if their flow into one water source is stopped.

A health- and exposure-driven standard must be continuously assessed and implemented for PFASs found in North Carolina waters to protect individual and public health. In addition, the North Carolina General Assembly should continue to examine the risk of PFAS exposure and take proactive action to lessen the risk and subsequent health consequences. NCMJ

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