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Association between Perfluorinated Compounds and Pathological Conditions in Southern Sea Otters

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Concentrations of four perfluorinated contaminants, including perfluorooctanesulfonate (PFOS) and perfluorooctanoic acid (PFOA), were measured in liver tissue from 80 adult female sea otters collected from the California coast during 1992−2002. Concentrations of PFOS and PFOA were in the ranges of <1−884 and <5−147 ng/g, wet wt, respectively. Concentrations of PFOA in the livers of these sea otters were among the highest values reported for marine mammals to date. Liver tissue from 6 male sea otters also was analyzed and contained significantly higher concentrations of PFOS than did tissues from female otters. To examine the association between exposures and potential effects, concentrations of PFOS and PFOA were compared among the adult female otters that died from infectious diseases, noninfectious causes, and from apparent emaciation. Concentrations of both PFOA and PFOS were significantly higher in sea otters in the infectious disease category than in the noninfectious category. Concentrations of PFOS and PFOA were not significantly different between noninfectious and emaciated otters, suggesting that the poor nutritive (body) status of emaciated otters did not affect the concentrations of perfluorochemicals in livers. Concentrations of PFOA increased significantly from 1992 to 2002, whereas PFOS concentrations increased from 1992 to 1998 and then decreased after 2000. Significant association between infectious diseases and elevated concentrations of PFOS/PFOA in the livers of sea otters is a cause for concern and suggests the need for further studies.

Introduction

Accumulation of perfluorinated compounds including perfluorooctanesulfonate (PFOS) and perfluorooctanoate (PFOA) in tissues of wildlife has been documented (*1*−*3*). Despite the widespread occurrence of perfluorinated acids in biota, little is known about the impact of these contaminants on the health of wildlife populations. PFOS and PFOA exert an array of toxic effects on exposed laboratory animals, including rodents (*4*−*7*), and fish (*8*, *9*). Toxicological studies have in general shown that PFOS and PFOA cause reductions in body weight and weight gain, increases in liver weight, peroxisome proliferation, increased incidence of hepatocellular adenoma, and hypocholesterolemia in exposed animals. Despite the reports of toxic effects of perfluorochemicals in exposed animals, field studies documenting effects in wildlife due to perfluorochemical exposures are meager. Fish and birds collected near a site contaminated with perfluorochemicals showed a positive correlation between PFOS concentration and biochemical perturbations including serum alanine aminotransferase activity (*10*, *11*).

Extrapolation of laboratory and surrogate-species data to free-ranging wildlife and establishment of a link between contaminant exposure and effects are challenging tasks. Contaminants exist in complex mixtures in the environment, and interactions can potentially occur among contaminants, nutritional status of animals, and other environmental factors. Although the cause−effect linkages are difficult to establish, correlative data on relationships between exposures and effects in wildlife, when applied cautiously, can provide baseline information that would allow us to develop a framework for future systematic investigations. One approach to study the relationship between exposures and effects is to compare residue levels of contaminants in diseased and healthy wildlife populations. Stranded carcasses in good postmortem condition or tissues of animals caught in gillnets or that were hunted can be used in such investigations. A necropsy can be conducted to detect abnormalities and to help determine the probable causes of death. Although several confounding factors such as co-exposure to a multitude of contaminants, and nutritional and environmental factors, may affect such relationships, as mentioned above, this indirect approach has been used in the past to investigate the prediction that increased exposure to toxic contaminants results in lowered resistance to infectious diseases in marine mammals (*12*, *13*).

In the recent past there has been a worldwide increase in diseases affecting marine organisms (*14*). The southern sea otter (*Enhydra lutris nereis*) population is one of the marine mammal populations reported to be affected by diseases and high mortality rates (*15*). The problems facing marine mammal populations, including the southern sea otters, are likely multi-factorial (*14*, *15*) and include effects from habitat destruction, pollutants, municipal runoff, global climate change, and over-harvesting of marine resources. In attempts to elucidate the relationship between pollutants and health of southern sea otters, earlier studies have reported exposure levels of several organic contaminants (*12*, *16*, *17*). Availability of large numbers of archived tissues from this species, which had been systematically examined for evidence of disease during post-mortem investigations and necropsy, provided an opportunity to evaluate the association between perfluorochemical concentrations and observed causes of mortality. In this study, concentrations of PFOS, PFOA, perfluorononanoic acid (PFNA), and perfluorohexanesulfonate (PFHS) were measured in livers of sea otters to compare exposure levels between individuals that died from infectious diseases and noninfectious causes.

Materials and Methods

Samples. A sample of adult female animals (n = 80) was selected from an archive of over 300 beached southern sea

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FIGURE 1. Map of California showing sampling locations of southern sea otters.

otters found freshly dead, between 1992 and 2002, along the central California coast (Figure 1). We chose samples based on gender and age so as to eliminate these as confounding factors. Additionally, female sea otters were chosen because of their more localized movement patterns, which make them more suitable indicators of local sources of pollution (*18*). Postmortem examinations were performed at the National Wildlife Health Center (NWHC) in Madison, Wisconsin, for the determination of cause of death (COD). The COD was classified, based on necropsy findings, into one of four categories: emaciation, infectious disease, other, and trauma (*19*). Each class is further divided into more specific subclasses. In this study, we grouped animals that died of infectious diseases into a "disease" group (n = 27), and animals that died from trauma and other causes into a "nondisease" group (n = 26). Otters that died in emaciated condition and had no evidence of other causes of death were grouped into a separate "emaciation" category (n = 27). It is likely that these animals died from emaciation due to inadequate food intake. However, other debilitating conditions not apparent by postmortem may also have been responsible for emaciation. The subclasses in this category are conditions that might have contributed to starvation, such as high demands of reproduction and dental disease, but these conditions alone were not expected to lead to fatal debility. The body condition was assessed based on the amount of adipose tissue and muscle mass, and was scored from 1 to 5: 1 for an animal in severely emaciated condition, 2 for poorly nourished, 3 for adequately nourished, 4 for well nourished, and 5 for an animal in excellent condition. Otters in the "infectious disease" category include those animals that died of acanthocephalan peritonitis (n = 3); protozoal encephalitis (n = 2); and fatal infections by bacteria (n = 14), fungi (n = 3), or parasites (n = 1). Also included in this category were other fatal cardiovascular (n = 2) and neurological (n = 2) infections. The category "other" comprised animals that died of gastrointestinal disorders (n = 5), miscellaneous individual problems (n = 3), neoplasia (n = 3), and from undetermined (n = 9) causes. The category "trauma" included otters that died from gun shot (n = 3) and shark bite (n = 3).

In addition to 80 adult female sea otters, six adult male sea otters collected during 1994−1999 from Moss Landing (Figure 1) were also analyzed, to allow us to assess the gender differences in the concentrations of perfluorochemicals. Three of the adult male sea otters died of infectious diseases, and the remaining animals (n = 3) died of trauma.

Liver samples were collected from the carcasses at the time of necropsy, wrapped in aluminum foil, enclosed in sterile sampling bags (TWIRL'EM, Fisher Scientific Inc., Hampton, NH), and stored at −20 °C until analysis. Concentrations of perfluorinated acids in liver tissue were determined by the ion pairing liquid extraction method described elsewhere (*2*). Briefly, each liver sample (0.3 g) was homogenized in 3 mL of Milli-Q water. A 2-mL aliquot of this homogenate was spiked with 5 ng of perfluorobutanesulfonate (PFBS) and 5 ng of ^{13}C−perfluorooctanoic acid (^{13}C−PFOA) as internal standards. One mL of 0.5 M tetrabutylammonium hydrogen sulfate solution, 2 mL of sodium carbonate buffer (0.25M, pH 10), and 5 mL of methyl-*tert*-butyl ether (MTBE) were added to the sample. After the sample was shaken for 30 min, the organic layer was separated by centrifugation, and the extraction was repeated with a further 5 mL of MTBE. The extracts were combined and evaporated to dryness under a gentle flow of nitrogen, before being reconstituted in 1 mL of methanol, and vortexed. The extract was filtered through a 0.2-μm nylon filter into an autosampler vial with a polypropylene cap.

Separation of perfluorinated acids was performed using an Agilent 1100 high-performance liquid chromatograph (HPLC). Ten μL of the extracts was injected onto a 50 × 2 mm (5 μm) Keystone Betasil C_{18} column. A gradient mobile phase of methanol and 2 mM ammonium acetate was used. At a flow rate of 300 μL/min, the mobile phase gradient was ramped from 10% to 25% methanol in 7 min and then to 100% methanol at 10 min, held at 100% methanol for 2 min, and then ramped down to 10% methanol. For quantitative analysis, the HPLC was interfaced with an Applied Biosystems API 2000 tandem mass spectrometer (MS/MS). The MS/MS was operated in negative electrospray ionization mode. Analyte ions were monitored using multiple reaction monitoring mode. Parent and daughter ion transitions monitored for detection of PFOS, PFHS, PFBS, ^{13}C−PFOA, PFOA, and PFNA were 499 > 99, 399 > 80, 299 > 80, 370>170, 369 > 169, and 462>219, respectively. Quantitation was performed using a linear regression fit analysis weighted $1/x$ of a single extracted calibration curve. Seven-point calibration curves were produced from concentrations of 0.1 to 100 ng/mL. The coefficient of determination (r^2) for each calibration was >0.99. Quality-control standards were measured after every 10 samples to check for instrumental drift. Analysis was stopped and a new calibration curve was run if the quality-control standard was not measured at ± 30% of its theoretical value. PFOA was found in procedural blanks and in methanol injections performed between samples. However, because this background PFOA signal was consistent, it was subtracted from the calibration curves and samples. Because PFOA contamination can also be introduced from fluoropolymer-containing vial caps (*20*), polypropylene or aluminum foil caps were used in this study.

All procedural blank peak areas were less than half the determined limit of quantitation (LOQ) for each analyte. The LOQ was estimated as three times the lowest concentration point on the calibration curve, which is accurately measured within ± 30% of its theoretical value. The LOQ was 5 ng/g for PFOA, and 1 ng/g for PFNA, PFOS, and PFHS. For statistical purposes, the LOQ values were assigned for those samples that contained concentrations below the limit of detection. Matrix spikes were performed for liver tissue samples by spiking 10 ng of each target analyte, and passing it through the whole analytical procedure. Recoveries of target analytes from the matrixes were between 80 and 102%. Recoveries of internal standards spiked to samples were 87 ± 10%. Concentrations are reported on a wet weight (wt) basis, unless specified otherwise. All statistical analyses were performed using Statgraphics ver 5 (Manugistics, Inc., Rockville, MD).

TABLE 1. Concentrations (ng/g, wet wt) of Four Perfluorochemicals in Livers of Adult Female Sea Otters from the California Coast by Mortality Categories[a]

statistic	PFOA	PFNA	PFOS	PFHS
Nondisease ($n = 26$)				
mean ± SD	48.9 ± 31.4	1.81 ± 1.90	30.9 ± 27.2	<1
median	59.5	<1	23.0	<1
min−max	<5−98	<1−9	<1−102	<1
Infectious- Disease ($n = 27$)				
mean ± SD	68.9 ± 26.3	2.1 ± 2.1	95 ± 166 [65][b]	<1
median	68	1.00	41	<1
min−max	<5−139	<1−8	5−884	<1
Emaciation ($n = 27$)				
mean ± SD	62 ± 35.5	2.44 ± 3.2	38.7 ± 37.1	<1
median	59.5	1.0	23	<1
min−max	<5−147	<1−16	4−169	<1
Overall ($n = 80$)				
mean ± SD	60 ± 32	2.1 ± 2.5	55 ± 104 [45][b]	<1
median	65	1.0	33	<1
min−max	<5−147	<1−16	<1−884	<1

[a] Nondetects were assigned the value of LOQ for calculation of mean and median. [b] Mean after removal of the outlier.

Results and Discussion

Residue Concentrations. Of the four perfluorochemicals analyzed in livers of 80 adult female sea otters, mean concentrations of PFOA were the highest, followed by PFOS and PFNA (Table 1). Overall, the mean concentration of PFOA was 60 ng/g, wet wt, and that of PFOS was 55 ng/g, wet wt. Because PFHS was not detected in any of the samples at a detection limit of 1 ng/g, it was subsequently dropped from any further analysis. The occurrence of higher concentrations of PFOA than PFOS was a finding different from what was observed in earlier studies, which have reported severalfold higher concentrations of PFOS than PFOA in biological matrixes, particularly marine mammals (*2*, *21*, *22*). Predominance of PFOA in sea otters suggests the existence of specific sources of this compound in coastal California, and/or specific feeding habits of sea otters. Sea otters feed on mollusks, crustaceans, and various sessile and slow-moving benthic invertebrates. Concentrations of PFOA in sediments and benthic invertebrates were greater than those of PFOS in a tidal flat ecosystem in Japan (*24*). It is probable that both the occurrence of local sources and the feeding habits of sea otters have contributed to these animals' elevated exposure to PFOA along the California coast. Further studies are needed to analyze the concentrations of perfluorochemicals in prey items of sea otters.

Concentrations of PFOA in sea otters ranged from <5 to 147 ng/g, wet wt (median 65; mean 60 ± 32). PFOA was found in 82% of the samples analyzed at concentrations above 5 ng/g, wet wt. PFOA was below the limit of detection in 8 of 15 sea otters that were classified as nondiseased. All of the top 5% of the PFOA concentrations, ranging from 110 to 147 ng/g, wet wt, occurred in diseased sea otters. PFOA concentrations in these sea otters were some of the highest values reported for a marine mammal species to date and were severalfold greater than those reported for polar bears and other marine mammals and sea turtles collected from various locations (Figure 2) (*2*, *21*−*29*). Occurrence of relatively high concentrations of PFOA in other marine mammals such as harbor seals, elephant seals, and California sea lions collected from the California coast suggests the existence of sources of PFOA in this area.

Concentrations of PFOS in sea otters ranged from <1 to 884 ng/g, wet wt (median 32.5; mean 55.1 ± 105) (Table 1). All but one sample had detectable concentrations of PFOS. The highest concentration of PFOS was found in a sea otter beached in May 1993, dying of a neurological infectious disease. The highest concentration of PFOS, 884 ng/g, qualified as an outlier, and was therefore omitted from further statistical analysis (unless specified otherwise). Concentrations of PFOS in sea otters in this study were 2-fold greater than those reported for California sea lions and harbor seals from the California coast (*2*) and for ringed seals from the Canadian Arctic (*22*). PFOS concentrations in these sea otters were lower than concentrations reported for marine mammals, mink, and river otters from several other locations (Figure 2) (*22*−*27*).

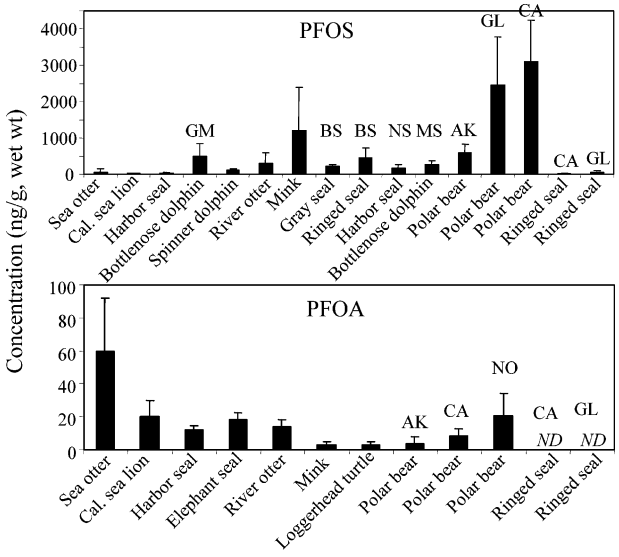

FIGURE 2. Mean (±SD) concentrations of PFOS and PFOA in livers of marine mammals from selected locations. Sea otter, harbor seal, California sea lion, elephant seal are from coastal California (data from ref *2*). River otters are from Washington and mink are from Illinois (data from *23*). BS refers to Baltic Sea and MS refers to Mediterranean Sea (data from *21*), NS refers to North Sea (data from *26*); AK is for Alaska (data from *25*), GL is for Greenland, CA stands for Canadian Arctic, and NO stands for Norway (data from *22*, *27*, *28*). Data for loggerhead sea turtle from the southern U.S. are from ref 29. ND = Not detected.

PFNA is an impurity in technical fluorochemical mixtures, and it is also a degradation product of fluorotelomer alcohols and fluoropolymers (*27*). PFNA was detected in only 19 of 80 samples. Concentrations of PFNA ranged from <3 to 16 ng/g, wet wt (median <3; mean 2.5 ± 2.3). Of the 19 sea otters having detectable concentrations of PFNA, 14 had been classified in the disease category. Few earlier studies have reported the occurrence of PFNA in marine mammals. Concentrations of PFNA found in sea otter livers in this study were 1−2 orders of magnitude lower than those reported for polar bears from the Arctic (*22*, *25*, *28*), but they were similar to concentrations reported for ringed seals from Greenland (*27*). Since the majority of our samples contained less than the LOQ for PFNA, further analysis of data was restricted to PFOS and PFOA.

Comparison of Otters in Disease, Emaciation, and Nondisease Categories. Concentrations of PFOS and PFOA in sea otters in the disease, emaciation, and nondisease mortality categories were compared using Fisher's least significant difference (LSD) procedure. Mean concentrations of PFOA in nondisease, emaciation, and disease categories were 49, 62, and 69 ng/g, wet wt, respectively (Table 1). Concentrations of PFOA were significantly higher in the disease group than in the nondisease group ($p < 0.05$; Kruskall−Wallis test). PFOA was below the limit of detection in 8 of 15 sea otters in the nondisease category. All of the top 5% of the PFOA concentrations, ranging from 110 to

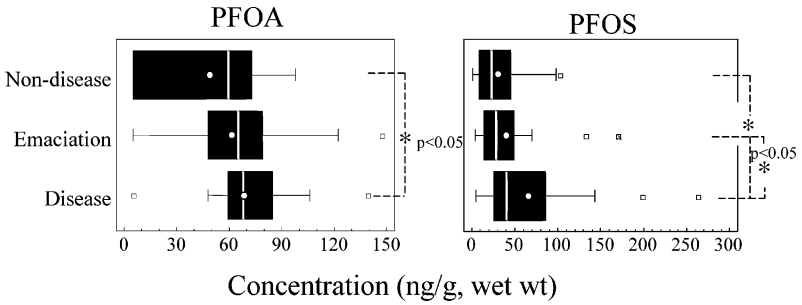

FIGURE 3. Box-and-whisker plots of PFOA and PFOS concentrations in livers of sea otter classified in "disease"' ($n = 27$), "emaciation" ($n = 27$), and "nondisease" ($n = 26$) mortality categories. An outlier for PFOS was removed in the disease category, so $n = 26$. Nondetects were assigned the LOQ value. White line is the median and white circle is the mean; lower and upper limits of the box represent 25th and 75th percentiles; the whiskers extend to the last observation within 1.5 times the interquartile range.

TABLE 2. Spatial (North to South) Differences in the Concentrations (ng/g, wet wt) of Perfluorochemicals in Livers of Adult Female Sea Otters from the California Coast[a]

	PFOA	PFNA	PFOS
	North of Seaside ($n = 7$)		
mean ± SD	68 ± 32	1.4 ± 1	49 ± 53
median	70	1.0	29
min−max	<5.0−110	<1.0−4.0	8.0−169
	Seaside to Cayucos ($n = 48$)		
mean ± SD	58 ± 30	1.9 ± 2.7	65 ± 130 [48][b]
median	65	1.0	33.5
min−max	<5.0−139	<1.0−16	<1.0−884
	South of Cayucos ($n = 25$)		
mean	62 ± 36	2.6 ± 2.2	38 ± 33
median	65	1.0	27.0
min−max	<5.0−147	<1.0−8	4.0−138

[a] Nondetects were assigned the value of LOQ for calculation of mean and median. [b] Mean after removal of the outlier.

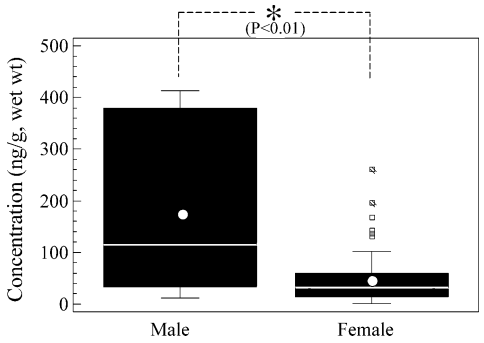

FIGURE 4. Box-and-whisker plots of PFOS concentrations in male ($n = 6$) and female ($n = 79$) sea otter livers. An outlier for PFOS was removed in the diseased category. Nondetects were assigned the LOQ value.

147 ng/g, wet wt, occurred in sea otters in the disease group. Mean concentrations of PFOS in nondisease, emaciation, and disease sea otters were 31, 39, and 65 ng/g, wet wt, respectively (Figure 3). Concentrations of PFOS in the disease group were significantly greater than those found in the nondisease and emaciation groups (outlier removed; $p = 0.04$, Kruskall−Wallis test) (Figure 3).

Whereas the significant association of elevated concentrations of PFOS or PFOA with "diseased" status in sea otters is remarkable, it is not known whether the elevated concentrations of PFOS and PFOA in "disease" otters were a cause of the disease, a consequence, or coincidental. The concentrations of both PFOS and PFOA in sea otters are much lower than the concentrations that have been reported to elicit toxic effects in laboratory animals. Laboratory studies on rats, monkeys, and birds have shown that toxic effects of PFOA and PFOS occur at tissue concentrations in the range of a few tens to hundreds of μg/g, wet wt (*5*, *6*, *30*). Residue concentrations of PFOS and PFOA in our sea otter livers were approximately 2−3 orders of magnitude lower than the effect concentrations found in laboratory animals. However, the laboratory toxicity studies have focused primarily on reproductive and developmental effects, with little attention paid to the immunotoxic effects of perfluorochemicals. Exposure of rats to PFOA resulted in the suppression of genes involved in inflammation and immunity (*31*). PFOA and PFOS are peroxisome proliferators, and they elicit potent immunomodulating effects in mice, involving thymic and splenic atrophy, loss of thymocytes and splenocytes, and potent suppression of adaptive immune responses (*32*). Further studies are needed on the immunotoxic effects of perfluorochemicals, and also on the interaction between perfluorochemicals and other contaminants that are found in sea otter tissues.

Another possible explanation for the high concentrations of perfluorochemicals in otters in the disease category, relative to the nondisease category, is mobilization of these contaminants from storage sites as a consequence of starvation, in the "disease" animals. High concentrations of lipophilic contaminants such as PCBs and DDT in stranded, diseased marine mammals have been attributed to increased lipid mobilization prior to the animals' death (*33*). Nevertheless, the lack of significant difference in PFOS and PFOA concentrations between "nondisease" and "emaciation" otters (Figure 3) in our study suggests that nutritive (body) condition did not influence the hepatic concentrations of perfluorochemicals in sea otters. This is plausible because perfluorochemicals, unlike PCBs and DDT, are not lipophilic and do not concentrate in lipid-rich tissues. Therefore, lipid mobilization due to starvation has little effect on perfluorochemical distribution in the body. Lack of correlation between blubber thickness and perfluorochemical concentration in bottlenose dolphin was reported recently (*34*).

To examine the influence of nutritive (body) condition on perfluorochemical concentrations, we grouped sea otters as emaciated ($n = 26$), poor ($n = 20$), adequate ($n = 12$), good ($n = 20$), and excellent ($n = 1$), based on qualitative examination of the amount of adipose tissue and muscle mass, at the time of necropsy. Lack of significant difference in the concentrations of PFOS and PFOA ($p > 0.05$; Mann−Whitney U test) among the various nutritional groups (Figure S1, Supporting Information), suggests that body condition did not influence the concentrations of perfluorochemicals in stranded sea otters or vice versa.

Comparisons of Otters by Location, Gender, Season, and Through Time. The effect of stranding location on the concentrations of PFOS and PFOA was tested using one-way ANOVA. For this analysis, sea otters' present-day range was divided into three categories; north of Seaside, Seaside-Cayucos, and south of Cayucos (Table 2). The three categories were chosen based on past studies (*35*), natural division of

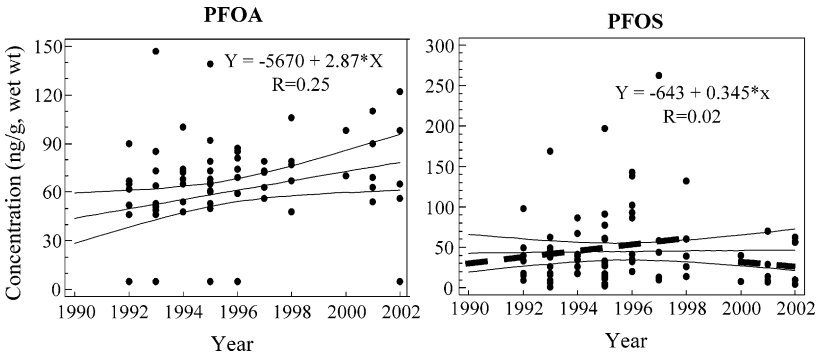

FIGURE 5. Temporal trends in PFOA and PFOS concentrations in livers of sea otters from the California coast from 1992 to 2002. Dotted line in PFOS panel suggests trends from 1992 to 1998, and from 2000 to 2002.

the developed coastline, and availability of data for each category. Due to the clustering of female sea otters in the center of the range and the dominance of males in the outer regions, lower numbers of female samples exist for the north of Seaside and south of Cayucos categories than for the central corridor. When the 80 adult female samples were tested, no significant difference was observed in PFOS and PFOA concentrations ($p > 0.05$) among the locations (Table 2). This suggests that contamination by PFOA and PFOS is widespread along the length of the central California coast.

Gender difference in the concentrations of PFOS and PFOA was examined by analysis of livers from six adult male sea otters collected from Moss Landing (north of Seaside) and the results were compared with the concentrations measured in the 80 adult female sea otters. PFOA was not found in adult male sea otters, at a detection limit of 5 ng/g. Reasons for the lack of detection of PFOA in male sea otters are not known. Small number of samples analyzed, diet, gender related excretion or migratory habits may be contributing factors. Concentrations of PFOS in male sea otters (range 11 to 413; mean 178; median 115 ng/g, wet wt) were significantly greater than those found in livers of female sea otters ($p < 0.05$; Mann−Whitney U test) (Figure 4). These results suggest transfer of PFOS from adult females during parturition and lactation to their offspring. Occurrence of perfluorochemicals in the milk of marine mammals (*34*) supports the idea of binding of PFOS to milk proteins and lactational transfer of these contaminants from mothers to offspring. Adult female California sea otters reproduce annually, and the protein content of the milk of otters has been found to range from 9 to 12% (*36*). The active reproductive cycle and high protein content in the milk of sea otters suggest transfer of high burdens of perfluorochemicals from adult female otters to their young.

Studies have shown that the mortality of sea otters is pronounced during the spring and summer months (*35*). To examine the relationship between perfluorochemical concentrations and stranding season, we compared concentrations of perfluorochemicals measured in otters stranded during spring and summer (April−August) to concentrations in otters stranded during fall and winter (September−March) (Figure S2, Supporting Information). Mean concentrations of PFOA and PFOS in sea otters stranded in spring/summer were 63 and 37 ng/g, wet wt, respectively, whereas those stranded in fall/winter were 57 and 51 ng/g, wet wt, respectively. Hepatic concentrations of PFOA and PFOS in sea otters did not vary significantly between the seasons ($p > 0.05$, Kolmogorov−Smirnov Test) (Figure S2, Supporting Information). There was lack of a significant relationship between the concentrations of PFOS and PFOA in livers of sea otters ($p > 0.05$), suggesting that the sources of these two perfluorinated acids are independent.

Because the adult female sea otter samples analyzed in this study originated from 1992 to 2002, temporal trends in the concentrations of perfluorochemicals could be examined for that decade. Concentrations of PFOA in sea otters increased significantly from 1992 to 2002 ($p < 0.05$; one way ANOVA, F-test) (Figure 5). However, no significant increase in the concentration of PFOS was found between 1992 and 2002. Nevertheless, when PFOS concentrations for 1992 to 1998 were compared, a significant ($p < 0.05$; one way ANOVA, F-test) increase was found. Mean concentration of PFOS in sea otters collected from 1992 to 1998 ($n = 67$) was 60 ± 20 ng/g, wet wt, and the mean concentration in sea otters collected from 2000 to 2002 ($n = 12$) was 29 ± 6 ng/g, wet wt. This suggests a reduction in PFOS concentrations in sea otters after 2000. No such reduction was found for PFOA. The reduction in PFOS concentrations in sea otters coincides with the voluntary phase-out of PFOS-based fluorochemicals in 2001 by the 3M Company, one of the major producers of fluorochemicals. Lake trout collected from Lake Ontario showed a 4-fold increase in PFOS concentrations from 1980 to 2001 (*3*). Guillemot eggs collected from the Baltic Sea showed an increase in PFOS concentrations from the 1960s until 2002, followed by a decrease until 2004 (*37*). PFOS and PFOA concentrations in ringed seals from Greenland increased significantly from 1982 to 2003 (*27*). The decline in concentrations of PFOS after 2002 suggests that environmental release of PFOS is decreasing.

Overall, our results suggest that the livers of sea otters from California contain among the highest concentrations of PFOA reported to date for marine mammals. Elevated concentrations of PFOA in sea otters and other marine mammals from the California coast suggest the existence of potential sources in the region. Concentrations of both PFOS and PFOA were significantly associated with presence of disease mortality in the sea otters. Whereas these findings indicate an association, establishment of the cause−effect linkage will require toxicological and controlled animal feeding studies. Contributions of and association with other contaminants such as PCBs, butyltins, and DDT to diseases in sea otters should not be overlooked; the concentrations of these contaminants have earlier been found to be elevated in sea otters (*12*, *16*, *17*). The trend of increase in the concentrations of PFOA in sea otters from 1992 to 2002 is of concern; efforts should be made to reduce emissions. Further studies are needed to confirm the trend of decline in the concentration of PFOS in the environment.

Acknowledgments

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Supporting Information Available

Box-and-whisker plots of PFOA and PFOS concentrations in sea otters stratified by nutritive condition, and in sea otters collected during high and low mortality seasons. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Giesy, J. P.; Kannan, K. Global distribution of perfluorooctane sulfonate and related perfluorinated compounds in wildlife. *Environ. Sci. Technol.* **2001**, *35*, 1339−1342.

(2) Kannan, K.; Koistinen, J.; Beckman, K.; Evans, T.; Gorzelany, J. F.; Hansen, K. J.; Jones, P. D.; Helle, E.; Nyman, M.; Giesy, J. P. Accumulation of perfluorooctane sulfonate in marine mammals. *Environ. Sci. Technol.* **2001**, *35*, 1593−1598.

(3) Martin, J. W.; Whittle, D. M.; Muir, D. C. G.; Mabury, S. A. Perfluoroalkyl contaminants in a food web from Lake Ontario. *Environ. Sci. Technol.* **2004**, *38*, 5379−5385.

(4) Lau, C.; Butenhoff, J. L.; Rogers, J. M. The developmental toxicity of perfluoroalkyl acids and their derivatives. *Toxicol. Appl. Pharmacol.* **2004**, *15*, 231−241.

(5) Kennedy, G. L.; Butenhoff, J. L.; Olsen, G. W.; O'Connor, J. C.; Seacat, A. M.; Perkins, R. G.; Biegel, L. B.; Murphy, S. R.; Farrar, D. G. The toxicology of perfluorooctanoate. *Crit. Rev. Toxicol.* **2004**, *34*, 351−384.

(6) Newsted, J. L.; Beach, S. A.; Gallagher, S. P.; Giesy, J. P. Pharmacokinetics and acute lethality of perfluorooctane-sulfonate (PFOS) to juvenile mallard and northern bobwhite. *Arch. Environ. Contam. Toxicol.* **2006**, *50*, 411−420.

(7) Molina, E. D.; Balander, R.; Fitzgerald, S. D.; Giesy, J. P.; Kannan, K.; Bursian, S. J. Effects of air cell injection of perfluorooctane sulfonate prior to incubation on the development of the white leghorn chicken (*Gallus domesticus*) embryo. *Environ. Toxicol. Chem.* **2006**, *25*, 227−232.

(8) Oakes, K. D.; Sibley, P. K.; Martin, J. W.; Maclean, D. D.; Solomon, K. R.; Mabury, S. A.; Van der Kraak, G. J. Short-term exposures of fish to perfluorooctanesulfonate: acute effects on fatty acyl-coA oxidase activity, oxidative stress, and circulating sex steroids. *Environ. Toxicol. Chem.* **2005**, *24*, 1172−1181.

(9) Ankley, G. T.; Kuehl, D. W.; Kahl, M. D.; Jensen, K. M.; Linnum, A.; Leino, R. L.; Villeneuve, D. A. Reproductive and developmental toxicity and bioconcentration of perfluorooctane-sulfonate in a partial life-cycle test with the fathead minnow (*Pimephales promelas*). *Environ. Toxicol. Chem.* **2005**, *24*, 2316−2324.

(10) Hoff, P. T.; Van de Vijver, K.; Dauwe, T.; Covaci, A.; Maervoet, J.; Eens, M.; Blust, R.; De Coen, W. Evaluation of biochemical effects related to perfluorooctane sulfonic acid exposure in organohalogen-contaminated great tit (*Parus major*) and blue tit (*Parus caeruleus*) nestlings. *Chemosphere* **2005**, *61*, 1558−1569.

(11) Hoff, P. T.; Van Campenhout, K.; Van de Vijver, K.; Covaci, A.; Bervoets, L.; Moens, L.; Huyskens, G.; Goemans, G.; Belpaire, C.; Blust, R.; De Coen, W. Perfluorooctane sulfonic acid and organohalogen pollutants in liver of three freshwater fish species in Flanders (Belgium): relationships with biochemical and organismal effects. *Environ. Pollut.* **2005**, *137*, 324−333.

(12) Kannan, K.; Guruge, K. S.; Thomas, N. J.; Tanabe, S.; Giesy, J. P. Butyltin residues in southern sea otters (*Enhydra lutris nereis*) found dead along California coastal waters. *Environ. Sci. Technol.* **1998**, *32*, 1169−1175.

(13) Bennett, P. M.; Jepson, P. D.; Law, R. J.; Jones, B. R.; Kuiken, T.; Baker, J. R.; Rogan, E.; Kirkwood, J. K. Exposure to heavy metals and infectious disease mortality in harbour porpoises from England and Wales. *Environ. Pollut.* **2001**, *112*, 33−40.

(14) Harvell, C. D.; Kim, K.; Burkholder, J. M.; Colwell, R. R.; Epstein, P. R.; Grimes, D. J.; Hofmann, E. E.; Lipp, E. K.; Osterhaus, A. D. M. E.; Overstreet, R. M.; Porter J. W.; Smith, G. W.; Vasta, G. R. Emerging marine diseases − climate links and anthropogenic factors. *Science* **1999**, *285*, 1505−1510.

(15) Schwartz, J.; Aldridge, B.; Blanchard, M.; Mohr, F. C.; Stott, J. The development of methods for immunophenotypic and lymphocyte function analyses for assessment of Southern sea otter (*Enhydra lutris nereis*) health. *Vet. Immunol. Immunopathol.* **2005**, *104*, 1−14.

(16) Nakata, H.; Kannan, K.; Jing, L.; Thomas, N.; Tanabe, S.; Giesy, J. P. Accumulation patterns of organochlorine pesticides and polychlorinated biphenyls in southern sea otters (*Enhydra lutris nereis*) found stranded along coastal California, USA. *Environ. Pollut.* **1998**, *103*, 45−53.

(17) Kannan, K.; Kajiwara, N.; Watanabe, M.; Nakata, H.; Thomas, N.; Stephenson, M.; Jessup, D. A.; Tanabe, S. Profiles of polychlorinated biphenyl congeners, organochlorine pesticides, and butyltins in southern sea otters and their prey. *Environ. Toxicol. Chem.* **2004**, *23*, 49−56.

(18) Ralls, K.; Eagle, T. C.; Siniff, D. B. Movement and special patterns of California sea otters. *Can. J. Zool.* **1996**, *74*, 1841−1849.

(19) Thomas, N. J.; Cole, R. A. The risk of disease and threats to the wild population. *Endangered Species Update* **1996**, *13*, 24−28.

(20) Yamashita, N.; Kannan, K.; Taniyasu, S.; Horii, Y.; Okazawa, T.; Petrick, G.; Gamo, T. Analysis of perfluorinated acids at parts-per-quadrillion levels in seawater using liquid chromatography-tandem mass spectrometry. *Environ. Sci. Technol.* **2004**, *38*, 5522−5528.

(21) Kannan, K.; Corsolini, S.; Falandysz, J.; Oehme, G.; Focardi, S.; Giesy, J. P. Perfluorooctanesulfonate and related fluorinated hydrocarbons in marine mammals, fishes, and birds from coasts of the Baltic and the Mediterranean Seas. *Environ. Sci. Technol.* **2002**, *36*, 3210−3216.

(22) Martin, J. W.; Smithwick, M. M.; Braune, B. M.; Hoekstra, P. F.; Muir, D. C. G.; Mabury, S. A. Identification of long chain perfluorinated acids in biota from the Canadian Arctic. *Environ. Sci. Technol.* **2004**, *38*, 373−380.

(23) Kannan, K.; Newsted, J.; Halbrook, R. S.; Giesy, J. P. Perfluorooctanesulfonate and related fluorinated hydrocarbons in mink and river otters from the United States. *Environ. Sci. Technol.* **2002**, *36*, 2566−2571.

(24) Nakata, H.; Kannan, K.; Nasu, T.; Cho, H.-S.; Sinclair, E.; Takemura, A. Perfluorinated contaminants in sediments and aquatic organisms collected from shallow water and tidal flat areas of the Ariake Sea, Japan: Environmental fate of PFOS in aquatic ecosystems. *Environ. Sci. Technol.* **2006**, *40*, 4916−4921.

(25) Kannan, K.; Yun, S. H.; Evans, T. J. Chlorinated, brominated and perfluorinated contaminants in livers of polar bears from Alaska. *Environ. Sci. Technol.* **2005**, *39*, 9057−9063.

(26) Van de Vijver, K. I.; Hoff, P.; Das, K.; Brasseur, S.; Van Dongen, W.; Esmans, E.; Reijnders, P.; Blust, R.; de Coen, W. Tissue distribution of perfluorinated chemicals in harbor seals (*Phoca vitulina*) from the Dutch Wadden Sea. *Environ. Sci. Technol.* **2005**, *39*, 6978−6984.

(27) Bossi, R.; Riget, F. F.; Dietz, R. Temporal and spatial trends of perfluorinated compounds in ringed seal (*Phoca hispida*) from Greenland. *Environ. Sci. Technol.* **2005**, *39*, 7416−7422.

(28) Smithwick, M.; Mabury, S. A.; Solomon, K. R.; Sonne, C.; Martin, J. W.; Born, E. W.; Dietz, R.; Derocher, A. E.; Letcher, R. J.; Evans, T. J.; Gabrielsen, G. W.; Nagy, J.; Stirling, I.; Taylor, M. K.; Muir, D. C. G. Circumpolar study of perfluoroalkyl contaminants in polar bears (*Ursus maritimus*). *Environ. Sci. Technol.* **2005**, *39*, 5517−5523.

(29) Keller, J. M.; Kannan, K.; Taniyasu, S.; Yamashita, N.; Day, R. D.; Arendt, M. D.; Segars, A. L.; Kucklick, J. R. Perfluorinated compounds in the plasma of loggerhead and Kemp's Ridley turtles from the southeastern coast of the United States. *Environ. Sci. Technol.* **2005**, *39*, 9101−9108.

(30) Butenhoff, J. L.; Kennedy G. L., Jr.; Frame, S. R.; O'Connor, J. C.; York, R. G. The reproductive toxicology of ammonium perfluorooctanoate (APFO) in the rat. *Toxicology* **2004**, *196*, 95−116.

(31) Guruge, K. S.; Yeung, L. W. Y.; Yamanaka, N.; Miyazaki, S.; Lam, P. K. S.; Giesy, J. P.; Jones, P. D.; Yamashita, N. Gene expression profiles in rat liver treated with perfluorooctanoic acid (PFOA). *Toxicol. Sci.* **2006**, *89*, 93−107.

(32) Yang, Q.; Xie, Y.; Alexson, S. E. H.; Nelson, B. D.; DePierre, J. W. Involvement of the peroxisome proliferators-activated receptor alpha in the immunomodulation caused by peroxisome proliferators in mice. *Biochem. Pharmacol.* **2002**, *63*, 1893−1900.

(33) Hobbs, K. E.; Muir, D. C. G.; Michaud, R.; Béland, P.; Letcher, R. J.; Norstrom, R. J. PCBs and organochlorine pesticides in blubber biopsies from free-ranging St. Lawrence River Estuary beluga whales (*Delphinapterus leucas*), 1994−1998. *Environ. Pollut.* **2002**, *122*, 291−302.

(34) Houde, M.; Wells, R. S.; Fair. P. A.; Bossart, G. D.; Hohn, A. A.; Rowles, T. K.; Sweeney, J. C.; Solomon, K. R.; Muir, D. C. G. Polyfluorinated alkyl compounds in free-ranging bottlenose dolphins (*Tursiops truncatus*) from the Gulf of Mexico and the Atlantic Ocean. *Environ. Sci. Technol.* **2005**, *39*, 6591−6598.

(35) Estes, J. A.; Hatfield, B. B.; Ralls, K.; Ames, J. Causes of mortality in California sea otters during periods of population growth and decline. *Mar. Mamm. Sci.* **2003**, *19*, 198−216.

(36) Riedman, M. L.; Estes, J. A. *The Sea Otter (Enhydra lutris): Behavior, Ecology and Natural History*; Biological Report 90 (14); U.S. Department of Interior: Washington, DC, 1990.

(37) Holmström, K. E.; Järnberg, U.; Bignert, A. Temporal trends of PFOS and PFOA in guillemot eggs from the Baltic Sea, 1968−2003. *Environ. Sci. Technol.* **2005**, *39*, 80−84.

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