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Personal exposure to benzene from fuel emissions among commercial fishers: comparison of two-stroke, four-stroke and diesel engines

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Commercial fishers are exposed to unburned hydrocarbon vapors and combustion products present in the emissions from their boat engines. The objective of this study was to measure personal exposure to benzene as a marker of fuel exposure, and to predict exposure levels across categories of carbureted two-stroke, four-stroke and diesel engines. A self-monitoring approach, employing passive monitors, was used to obtain measurements of personal exposure to benzene over time. Mixed-effect linear regression models were used to predict exposure levels, identify significant effects and determine restricted maximum likelihood estimates for within- and between-person variance components. Significant fixed effects for engine type and refueling a car or truck were identified. After controlling for refueling, predicted benzene exposure levels to fishers on boats equipped with two-stroke, four-stroke and diesel engines were 58.4, 38.9 and 15.7 μg/m^3, respectively. The logged within-person variance component was 1.43, larger than the between-person variance component of 1.13, indicating that the total variation may be attributable to monitor placement, environmental conditions and other factors that change over time as well as differences between individual work practices. The health consequences of exposure to marine engine emissions are not known. The predicted levels are well below those at which health effects have been attributed, however.
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Introduction

Commercial fishers are exposed to unburned hydrocarbon vapors and combustion products present in the emissions from their diesel- or gasoline-powered boat engines. Gasoline and diesel fuel, both hydrocarbon mixtures, contain a host of possible and known neurotoxic agents. They differ with regard to their vapor pressure, relative proportion of aromatics and associated health effects, however. Gasoline is highly volatile, typically containing between 25 and 30% aromatic hydrocarbons, many of which are known to produce neurotoxic responses (Ritchie et al., 2001). By contrast, diesel fuel is distilled to exclude the aromatics and has a negligible vapor pressure at normal ambient temperatures. Unburned diesel fuel in the exhaust adsorbs onto the particles formed during combustion, however.

Although most of the neurotoxic effects associated with organic solvent mixtures including fuel and constituents of fuel, have been observed among highly exposed painters, carpet layers, printers and jet fuel workers (Baker and Fine, 1986; Baker, 1994; Broadwell et al., 1995; Escalona et al., 1995; Tsai et al., 1997), workers, such as fishers with potentially lower exposure may also experience neurotoxic effects. The study of health effects associated with low-level occupational exposure to fuel presents methodological challenges because it is difficult to determine an appropriate unexposed comparison group.

The health hazards typically associated with exposure to the particulate matter in diesel exhaust are lung cancer and respiratory disease (NIOSH, 1988). Gasoline exposure is associated with renal and liver cancer, acute myeloid leukemia (AML), myeloma, heart disease and irritant effects (reviewed by Caprino and Togna (1997)). Benzene, which is present in liquid gasoline at much higher concentrations than in diesel fuel and is produced during the combustion of both fuels, is causally associated with AML in occupational groups exposed to relatively high levels (>10 PPM or 32 mg/m^3) (Infante et al., 1982; Wong, 1995; Savitz and Andrews, 1997).

Our objectives were to measure benzene as a marker of fuel exposure among commercial fishers over time, and identify the determinants of this exposure. We conducted this study to identify differences in exposure that may explain variation in

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neuropsychological test outcomes measured as part of a longitudinal cohort study of commercial fishers (Moe et al., 2001). Although we anticipated that commercial fishers would be exposed to relatively low levels of benzene from fuel emissions, we expected to observe differences in exposure related to the type of engine used during fishing. Specifically, we expected fishers who use carbureted two-stroke engines to have higher hydrocarbon exposures than those who use diesel engines or less polluting four-stroke engines. Two-stroke engines release high levels of hydrocarbons because oil is mixed with the fuel to lubricate the piston and the fuel intake and exhaust ports are open simultaneously during a portion of compression–combustion cycle. Hydrocarbon emissions per kilogram of fuel consumed are approximately 60 to 100 times greater for snowmobiles with two-stroke engines than for gasoline-powered cars and diesel buses (Bishop et al., 2001). The United States Environmental Protection Agency (US EPA) estimates that the new generation of four-stroke and fuel-injected two-stroke engines will reduce hydrocarbon emissions by 75% compared to current two-stroke engines (US EPA, 1996).

No previous studies evaluating personal exposure, rather than emissions characteristics, among those using two-stroke engines were identified through this literature review. Unlike recreational users of two-stroke engines or those who operate lawnmovers or other power tools with two-stroke engines, commercial fishers may be at particular risk because they breathe emissions from their boat engines all day, several days per week, during their entire working life.

Methods

Data Collection

The population for this fuel exposure study consisted of commercial fisher participants throughout the coastal region of North Carolina enrolled in an ongoing longitudinal cohort study conducted by researchers at the University of North Carolina at Chapel Hill (Moe et al., 2001). Each of the 238 participants in the cohort study received a clinical examination every 5 to 7 months during a nearly 2.5-year follow-up period. During this exam, clinic staff asked participants if they were interested in measuring their benzene exposure and obtained informed consent from those choosing to participate. The project was piloted in January of 2001 to test the monitoring methods in the field and assess the time burden to participants. The official monitoring period extended from 17 June 2001 through 10 October 2001. An incentive of $25.00 was offered for each monitor returned for analysis.

An initial self-monitoring kit, adapted from that developed by Egeghy et al. (2000), containing a passive monitor, written instructions on how to use the monitor, a questionnaire on work practices and equipment, and a stamped and addressed envelope for returning the monitor for laboratory analysis was provided to each participant during the exam. The correct use of the monitor was demonstrated at this time. The participant was simply required to open the cap, record the time, attach the monitor to his or her shirt collar, then close the cap tightly at the end of the sampling period and record the time. The participant was instructed to use the monitor the next time he or she fished or did mechanical work, measure exposure for a complete workday including lunch and breaks, fill out the work activity questionnaire and mail the monitor back for analysis. The questionnaire consisted of an open-ended work activity log for the monitoring day, a checklist to record the type(s) of fishing performed and questions designed to capture information to explain the variation in observed exposure levels (see listing of potential determinants of exposure in data analysis section).

In order to characterize the temporal variation in exposure, participants were asked to make at least two measurements. Those who returned the first monitor received a letter with a randomly selected date (through the projected close of the study on 31 October 2001) for a second day of sampling. When the selected date approached, attempts were made to contact the participant so that interest could be assessed and a monitoring kit could be mailed. Similarly, attempts to contact those who returned a second monitor were made so that a third monitor could be mailed. To maximize the number of measurements made, we ceased the random selection of dates for repeat measurements near the end of the study and asked those who could be reached by telephone to perform additional monitoring. Individual results were mailed to each participant and follow-up telephone interviews were conducted to answer questions and to obtain missing data.

Analysis of Monitors

Benzene monitoring and analytic methods are described in detail elsewhere (Egeghy et al., 2000). Passive monitors consisting of aluminum tubes packed with 0.1 g of Tenax (SKC Inc., Eighty Four, PA, USA) were assembled. Monitors were initially conditioned at 250°C for 30 min using the Perkin Elmer ATD 400 automatic thermal desorption system to clean the reusable sampling medium and remove residual benzene. Prior to distribution for field use, monitors were conditioned again at 225°C for 3 min. Returned monitors were desorbed with the ATD 400 and analyzed with a Hewlett Packard 6890 Series II gas chromatograph (Hewlett-Packard Corp., Palo Alto, CA, USA) with HNU PI-52-02-A photo ionization detector (HNU Systems, Inc., Newton, MA, USA). Separation was accomplished with a megabore DB-1, 60-m × 0.53-mm dimethylpolysiloxane column. (1.5 μm film thickness) (J&W Scientific, Folsom, CA, USA).

External calibration standards were prepared by drawing known quantities of benzene vapor diluted in zero-grade air through passive monitors at approximately 60 ml/min using a needle valve regulated vacuum line. Calibration curves with at least five points were determined by least squares linear regression. The limit of quantitation (LOQ) was estimated as three times the average size of a residual benzene peak from analysis of conditioned air samplers.

Statistical Analysis

Data from both the pilot and the continuation phase where included in this analysis. Benzene exposure level was standardized to an 8-h workday and natural log-transformed for all statistical analyses. Concentrations at or below the LOQ were assigned a value of 2/3 the LOQ prior to log transformation. A histogram was examined to identify influential outliers and confirm that the distribution of log-transformed benzene levels was approximately normal. Normality was also assessed using the Shapiro–Wilks test for normality (critical P-value = 0.05). The mixed-effects linear regression model described below was specified using the MIXED procedure in SAS version 8.01 (SAS Institute, Cary, NC, USA) to predict benzene level and obtain restricted maximum likelihood (REML) estimates of between- and within-person variances.

Mixed Effects Model

$$Y_{h(ij)} = \ln(X_{h(ij)}) = \mu_y + \alpha_h + \sum_{m=1}^{p} \delta_m C_{mh(ij)} + \beta_{h(i)} + \varepsilon_{h(ij)}$$

where,

$Y_{h(ij)} =$ the log-transformed exposure level on the *j*th day for the *i*th fisher and the *h*th engine type
$X_{h(ij)} =$ the untransformed exposure level on the *j*th day for the *i*th fisher and the *h*th engine type
$C_{mh(ij)} =$ the *m*th covariate on the *j*th day for the *i*th fisher and the *h*th engine type
$\mu_y =$ the overall mean log-transformed exposure level for all engine types
$\alpha_h =$ the fixed effect for engine type h
$\delta_m =$ the regression coefficient for each covariate
$\beta_{h(i)} =$ random effect for person (μ_{yhi}–μ_{yh}), $\sim$ N $(0,\sigma^2_{\mathrm{B}})$
$\varepsilon_{h(ij)} =$ random error for the *j*th observation on the ith fisher, $\sim$ N $(0,\sigma^2_{\mathrm{w}})$
$m =$ $1,2,\ldots,p$ covariates
$h =$ $1,2,\ldots,g$ engine types
$i =$ $1,2,\ldots,k$ workers in the *h*th engine type
$j =$ $1,2,\ldots,n$ measurements on the *i*th fisher in the *h*th engine type

Models were fit using methods described by Rappaport et al. (1999). Engine type (i.e. inboard diesel, four-stroke gasoline and two-stroke gasoline) was specified as the main fixed effect and likelihood ratio tests (based on the difference in the −2 Log Likelihood values were applied to determine whether within- and between-person variance could be pooled across engine types.

Ten potential determinants of exposure to benzene in fuel were identified, *a priori*, through a review of the literature (Wixtrom and Brown, 1992; US EPA, 1996; Wallace, 1996; Egeghy et al., 2000; Moe et al., 2001). These potential determinants were considered for inclusion in the full mixed-effects linear regression model as covariates (fixed effects). They were season, fuel type, refueling a car or truck, refueling a boat, boat size, cabin style, type of fishing, smoking, turning off the engine and average boat speed. The univariate distributions of each were examined and dichotomous variables were defined. Correlations between covariates were determined using Spearman correlation coefficients and the full model was specified. A backward selection strategy was employed to choose covariates for the final model. Only fixed effects with associated P-values of ≤ 0.05 were retained in the model. Once the final model was determined, the normality of the random effects was assessed qualitatively by examining the histogram and quantitatively with the Shapiro–Wilks test of normality.

Exclusions

Application of the mixed-effect linear regression model requires that the underlying distribution of the data is approximately normal and that random effects are normally distributed with a mean of 0 and a variance of σ^2_{B}. If the underlying distribution of the data is found to be approximately lognormal, the mean and variance of the log data can be used to estimate the mean and the variance of the untransformed data. Preliminary univariate analyses of these data indicated the presence of influential outliers that challenged these normality assumptions. As verification that participants followed the self-monitoring protocol was not possible, highly improbable observations were excluded. All measurements ($n = 5$) below the LOQ but made by participants who reported refueling their car or truck were deemed to be highly improbable. The LOQ of the analytic method was 1 μg/m^3 for an 8-h sampling period, and the adequacy for quantifying benzene exposure after only minutes of refueling has been demonstrated (Egeghy et al., 2002).

In addition, monitors that were returned without caps could not be used ($n = 2$) and six valid but unusable measurements were excluded. The valid but unusable measurements included those that could not be classified with regard to the main effect of engine type ($n = 2$), a measurement taken by a subject who worked a full day as a machinist before beginning his fishing work ($n = 1$), and measurements made while exclusively working on boat motors or mechanical equipment ($n = 3$).

Results

The initial participation rate, that is the proportion of those invited agreeing to participate, was high (88%) during the pilot (Table 1). Only 57 and 50 percent (first and second monitors, respectively) of those who were provided with a monitor during the pilot returned it for analysis. However, those who returned the monitor reported no difficulties using it, nor did they find the time commitment burdensome. During the continuation phase of the project, an effort was made to emphasize the importance of returning the monitor. During this phase of the project, the participation rate among those recruited at the clinic for their first measurement was lower (32%), while the return rate increased to 78% (Table 1). Overall, a total of 186 fishers were invited to participate in this study, 68 (40%) agreed to measure their fuel exposure and 50 (74%) returned at least one monitor (Table 1). Twenty-four (50%) participants provided two measurements and 11 (22%) provided three measurements (Table 1). A total of 117 monitors were distributed, 85 (73%) were returned and 74 (87%) were available for analyses after exclusions.

Responses from the open-ended work activity logs describing the workday while fishing ($n = 82$) are summarized in Table 2. Of the 85 logs returned with the monitors, three measurements made while the participant did not fish are not shown. Most participants reported some type of preparatory or post-fishing work. The other fishing related activities listed in the table are conducted intermittently during the fishing season.

Of the 74 valid and useable measurements (Table 3), information on covariates was missing for five measurements (7%). A total of 69 measurements among 45 fishers were included in the final mixed-effect linear regression analyses. The underlying distributions of the log-transformed benzene level and the random effects for subject were approximately normal after exclusions. There was only one repeated measurement in the diesel engine category and four in the four-stroke engine category. The within- and between-person variances could not be estimated independently for these groups so their variance components were pooled with the two-stroke engine group in the final model.

The highest log-benzene levels across all engine types are found when refueling was reported (Table 4). Each of the covariates listed in Table 4 was included in the full model. Cabin and boat size were not included because they were highly correlated with diesel engine. The questionnaire item concerning average boat speed did not yield useable data because most participants left the question blank. There were no reports of using chemicals during the monitoring day. The

Table 2. The mean number of hours worked on days described in 82 work activity logs kept by the participants while fishing, North Carolina, 2001

Work activity	Reported activity (*N*)	Mean (h/d ± SD)	Range (h)
Total workday[a]	82	8.0 (2.7)	3.3–14.5
Prepwork[b]	49	0.7 (0.6)	0.1–2.3
On the water work[c]	68	6.0 (1.9)	2.8–11.1
Post fishing work[d]	62	1.0 (0.6)	0.1–3.1
Fishing related work[e]	11	3.1 (3.0)	0.4–10.1
Non-fishing work[f]	4	5.5 (5.0)	0.8–11.0

[a] Does not include reported travel to and from dock or nonfishing work.
[b] Includes loading boat, unloading truck and filling gas tanks.
[c] Includes motoring to fishing grounds, fishing (pulling pots or nets, rebaiting), setting pots or nets, and working with catch.
[d] Includes unloading boat, loading truck, separating catch, preparation for the next day, selling catch and fueling boat.
[e] Includes work-related errands, repairing boats or equipment and seasonal work such as preparing nets, pots, lines or hooks and cutting net stakes.
[f] Includes housework, work as a machinist and grounds keeping.

Table 3. The number of subjects, measurements and geometric mean for personal benzene exposure level by engine type, North Carolina, 2001

Engine Type	Subjects (*N*)	Measurements (*N*)	GM (GSD)
2-Stroke	26	48	3.39 (1.89)
4-Stroke	13	17	3.60 (1.82)
Inboard diesel	8	9	1.87 (1.77)
Total	47	74	3.24 (1.91)

Table 1. The number of invitees, monitors distributed and monitors returned by the participants ($n = 50$), North Carolina, 2001

	Dates	1st monitor			2nd monitor		3rd monitor	
		Invited	Accepted	Returned	Contacted/accepted	Returned	Contacted/accepted	Returned
Pilot	January 5 to January 15	16	14 (88%)	8 (57%)	4	2 (50%)	2	1 (50%)
Continuation	June 17 to October 10	170	54 (32%)	42 (78%)	30	22 (73%)	13	10 (77%)
Total		186	68 (37%)	50 (74%)	34	24 (71%)	15	11 (73%)

Table 4. The distribution of potential determinants of exposure by engine type and the mean of log-transformed benzene exposure level, North Carolina, 2001

Determinant of exposure	2-Stroke ($N=37$) N, GM	4-Stroke ($N=13$) N, GM	Diesel ($N=5$) N, GM	All Engines ($N=55$) N, GM
Refuel car or truck				
Yes	12, 4.91	9, 4.68	2, 3.22	23, 4.68
No	32, 2.82	7, 2.22	7, 1.40	46, 2.51
Refuel boat with gasoline				
Yes	24, 4.40	8, 4.32	0	32, 4.38
No	22, 2.30	8, 2.89	9, 1.81	39, 2.31
Fall and winter[a]				
Yes	22, 3.62	6, 4.24	4, 3.15	32, 3.68
No	25, 3.18	10, 3.22	5, 0.72)	40, 2.88
Did motor work				
Yes	2, 3.68	1, 3.64	2, 3.06	5, 2.78
No	45, 3.37	15, 3.60	7, 1.90	67, 3.27
Smoked >10 cigarettes				
Yes	7, 3.46	2, 2.77	2, 1.94	11, 3.10
No	40, 3.37	14, 3.72	7, 1.77	61, 3.27
Motor off				
Yes	24, 3.54	7, 4.57	2, 2.49	33, 3.61
No	22, 3.23	9, 2.85	7, 2.02	38, 2.91
Type of fishing				
Crabbing	23, 3.79	12, 3.26	5, 1.43	40, 3.34
Finfishing	12, 2.73	1, 8.05	2, 3.08	15, 3.13
Shrimping	4, 2.67	1, 3.99	1, 3.63	6, 3.05
Clamming or oystering	7, 4.01	2, 3.23	0	9, 3.84

[a] Personal exposure to benzene in the fall and winter was expected to be higher than in the summer and spring due to variation of the benzene content in liquid gasoline. (Egeghy et al., 2000).

fixed effects for season, doing motor work in addition to fishing, and smoking were not significant predictors of exposure. Subjects who oystered or clammed reported keeping their motor off for relatively long periods (335 min on average) compared to finfishers (148 min on average) and shrimpers and crabbers (ran motor constantly). Fixed effects for oystering, clamming and turning off the engine were not significant predictors of exposure. Significant effects were engine type and refueling a car or truck. The interaction between engine type and boat refueling was not significant.

The results from the final mixed-effects linear regression model are in Table 5. The model was specified without an intercept; thus, the estimates listed in the table are the mean of the log-transformed data in micrograms per cubic meter (μg/m^3) for each of the engine type categories. The logged within-person variance component estimated by the model was similar in magnitude ($\sigma^2_{\mathrm{W}}=1.43$) to the logged between-person variance ($\sigma^2_{\mathrm{B}}=1.13$). The estimated means for the untransformed data, which rely on the underlying normality of the log-transformed data and the correct estimate for the total variance, are also listed. After controlling for refueling, there was a clear difference between engine type categories. The predicted mean personal exposure estimates for the fishing workday were 58.4, 38.9, and 15.7 μg/m^3 for two-stroke, four-stroke and diesel engines, respectively, when no car or truck refueling was done. The mean predicted personal exposure estimates for the workday were 377.4, 251.5 and 101.6 μg/m^3 for two-stroke, four-stroke and diesel engines, respectively, when car or truck refueling was also done.

Discussion

Commercial fishers work alone or in small groups in geographically diverse locations, posing a challenge for quantitative exposure assessment. To overcome this challenge, fishers enrolled in this study were trained to passive monitors, provided with monitoring kits and asked to measure their own exposure. This study provides evidence that personal exposure to benzene from fuel emissions is higher when operating a boat with a two-stroke engine compared to personal exposure when operating a four-stroke

Table 5. Point estimates, standard errors and *P*-values for fixed effects that explained some of the variance in the log-transformed benzene personal exposure level ($n = 35$ subjects, $n = 52$ observations), fuel study participants, North Carolina, 2001

Engine Type	Estimate	Standard error	*P*-value	Estimated mean (μg/m^3)[a]	
				Refuel = No	Refuel = Yes
2-Stroke ($\mu_y + \alpha 1$)[b]	2.7863	0.3038	<0.0001	58.4	377.4
4-Stroke ($\mu_y + \alpha 2$)[c]	2.3804	0.4960	<0.0001	38.9	251.5
Inboard Diesel ($\mu_y + \alpha 3$)[d]	1.4742	0.5624	0.0153	15.7	101.6
Refueling car or truck ($\delta 1$)[e]	1.8659	0.4361	0.0003		

[a] He predicted mean was estimated using the equation, $\mu_{x,h} = \exp(\mu_{y,h} + 0.5\,\sigma^2_{y,h})$, which relates the mean of the raw data ($\mu_{x,h}$) to the mean and variance of the log-transformed data ($\mu_{y,h}$ and $\sigma^2_{y,h}$). The total variance is the sum of the within- and between-person components ($\sigma^2_{yh} = \sigma^2_w + \sigma^2_B$). (Atchinson and Brown, 1957).

[b] $\mu_y + \alpha_1$ = geometric mean for the 2-stroke engine group.

[c] $\mu_y + \alpha_2$ = geometric mean for the 4-stroke engine group.

[d] $\mu_y + \alpha_3$ = geometric mean for the diesel engine group.

[e] δ_1 = fixed effect for refueling car or truck.

gasoline or diesel engine. Two-stroke engines are known to emit more unburned fuel (including benzene) than four-stroke or diesel engines, and the elevated personal exposures to benzene may also indicate higher levels of exposure to potentially neurotoxic hydrocarbons.

The self-monitoring approach for collecting personal exposure measurements has been used successfully in several previous studies (Loomis et al., 1994; Saarinen et al., 1998; Rappaport et al., 1999; Tielemans et al., 1999; Egeghy et al., 2000; Liljelind et al., 2000). Although our participants were trained to use passive monitors, we were not able to verify that they followed the self-monitoring protocol. Measurements that were below the LOQ (22%) were assigned a value of 2/3 the LOQ for the analysis. As the LOQ for our analytical methods was very low, it appeared that some of the monitors were used incorrectly. We excluded improbable below-LOQ observations for those who also refueled their car or truck ($n = 5$). In a model including these measurements a clear difference in two- and four-stroke engines was not observed. The parameter estimates for engine type were as follows: (1) 2.83, $P < 0.01$, two-stroke engine; (2) 2.85, $P < 0.01$, four-stroke engine; and (3) 1.16, $P = 0.06$, diesel engine. The fixed effect for refueling a car or truck was 1.09 and remained significant ($P = 0.02$). The normality assumption for the distribution of random effects was not met for this model suggesting poor model fit. Although our exclusions represented our best effort to include only high-quality data, we may have introduced bias into our results. However, the predicted exposure levels from both models were within the same order of magnitude and both models predicted a substantial difference in benzene exposure between gasoline and diesel engines.

In addition to the large proportion of measurements below the LOQ, one individual contributed three measurements that were in excess of 3000 μg/m^3 ($\sim$50 times the predicted exposure level for two-stroke engines). This individual reported refueling his car, truck and boat and used both two- and four-stroke engines. The wide range in measured exposure levels and presence of influential outliers may indicate that our sample was not drawn from one distribution. Unmeasured factors such as high wind velocity on boats may have altered the performance of the passive monitors explaining the low measurements, while specific work conditions or individual work practices may explain the high outlying measurements contributed by one fisher. The similar within- and between-person variance components indicate that both factors that change over time such as environmental conditions or monitor placement as well as factors related to the individual participant's work practices or working conditions are important explanatory factors for the large observed variability in personal exposure to benzene.

We do not think it is likely that observed variability in our results can be explained by the use of different formulas of gasoline. The proportion of benzene relative to other hydrocarbons may vary depending on the season, vender and grade of gasoline (Wixtrom and Brown, 1992). This variation was expected to be minimal because most measurements were made in the summer and fall and a fixed effect for season (comparing spring and summer levels to fall and winter levels) was not significant. Furthermore, discussions with individual fishers during telephone follow-up indicated that most participants purchased the cheapest fuel hence the octane grade should be similar across the measurements.

Although exposure to diesel fuel does represent a health hazard, benzene levels in diesel exhaust do not necessarily correspond to levels of other potentially neurotoxic substances. Liquid diesel fuel contains only trace amounts of aromatics such as benzene (Muzyka et al., 1998) and the benzene measured while fishing on a diesel boat is produced predominantly through combustion. Most of the hydrocarbons in diesel exhaust have low vapor pressures and are adsorbed onto the particulate matter. Benzene, which is more volatile, largely remains in the gaseous phase (Muzyka et al.,

1998) but does not indicate the presence of other volatile aromatic hydrocarbons that are likely to pose an inhalation risk to the nervous system.

Findings from the Total Exposure Assessment Methodology (TEAM) studies conducted by the US EPA in the 1980s as well as from more recent studies have estimated an average personal exposure to benzene of approximately 15 μg/m^3 in urban areas, while the average outdoor concentration is approximately 6 μg/m^3 in urban areas (Wallace 1996, 1989) and 1.3 μg/m^3 (Duarte-Davidson et al., 2001) in rural areas. The predicted exposure level for commercial fishers using two-stroke engines (58.4 μg/m^3) is about four times as high as the average urban personal exposure level and higher than in-vehicle exposure during rush hour traffic (40 μg/m^3) (Wallace, 1996; Duarte-Davidson et al., 2001). Refueling, which was identified as a significant fixed effect, has been shown in other studies to be an important source of personal exposure even though this activity takes only minutes (Backer et al., 1997; Vainiotalo et al., 1999; Egeghy et al., 2000).

Many constituent compounds in gasoline such as benzene, toluene, ethylbenzene and xylene, are known neurotoxic agents (Burbacher, 1993; Ritchie et al., 2001). However, the effect of simultaneous exposure to these agents is not known. Evidence from studies of animals shows the potential for synergistic or additive as well as antagonistic interactions among the individual components in fuel Ritchie et al. (2001). Relatively high exposure to gasoline is known to damage the central nervous system. Sniffing gasoline vapors is associated with ataxia, tremor and encephalopathic syndrome (Burbacher, 1993; Cairney et al., 2002). Exposure to gasoline (leaded and unleaded gasoline) among filling station attendants has been associated with effects on intellectual capacity, psychomotor and visuomotor function, immediate and delayed memory and increased mortality from mental disorders (Schwartz, 1987; Kumar et al., 1988; Burbacher, 1993; Ritchie et al., 2001). Personal benzene exposure among filling station attendants has been reported to be about 10 times more (0.55 mg/m^3) than that predicted for fishers operating boats with two-stroke engines (Lagorio et al., 1994). Acute effects on the central nervous system from breathing emissions on boats are not likely. The short-term threshold limit value established by the American Conference of Industrial Hygienists to protect against the acute neurotoxic effects of gasoline is 1480 mg/m^3 total hydrocarbons. As gasoline vapor typically consists of nearly 1% benzene (Reese and Kimbrough, 1993), we can infer that the total hydrocarbon exposure for commercial fishers is much lower than the short-term threshold limit value.

Benzene in fuel is of particular concern because it has been causally associated with acute myeloid leukemia (AML) but the disease risk at levels <32 mg/m^3 is not certain (Savitz and Andrews, 1997). There is inconclusive evidence regarding the AML risk for garage mechanics (Schwartz, 1987; Hansen, 1989; Loomis and Savitz, 1991; Hunting et al., 1995; Hotz and Lauwerys, 1997), whose current average personal exposure to benzene is reported to be approximately 100 μg/m^3 (Egeghy et al., 2002) or twice that predicted for fishers who use two-stroke engines.

Questions as to the quality of the data and correct use of the monitors point to the need to ensure adequate training as well as include a validation component in self-monitoring programs used for exposure assessments. Including larger numbers of subjects and more repeat measurements would have also improved our ability to accurately characterize personal exposure to benzene among commercial fishers using different types of engines. Random error that may have been introduced by day-to-day exposure variability, incorrect monitor placement or varying lengths of time between monitor preparation and monitor use would tend to attenuate associations between exposure estimates and health effects in epidemiologic studies, and could be counterbalanced through a larger study size. Nonetheless, this study suggests that personal exposure to benzene is higher while operating a fishing boat compared to background levels. The effects of benzene and other constituents of gasoline on human health at these levels are not known. However, the predicted levels are below those at which health effects can be reliably attributed.

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